Hamilton Standard
DIVISION OF UNITED AIRCRAFT CORPORATION

NASW-1271

STUDY TO RELATE APOLLO SPACE SUIT TECHNOLOGY TO THE FIELD OF HYPERBARIC MEDICAL THERAPY

Prepared for

OFFICE OF TECHNOLOGY UTILIZATION
NATIONAL AERONAUTICS & SPACE ADMINISTRATION
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March 25, 1966

SUMMARY CHART OF HARDWARE REQUIREMENTS FOR SYSTEM #3 OPEN-SYSTEM HYPERBARIC CHAMBER

Item	No. Required	Input Power Per Unit	Size Per Unit	Weight Per Unit	Possible Vendor (comment)
Air Compressor	2	8.2 hp	20" x 5" x 8"	8 lbs	Stratos (Model ACR5)
Compressor Motor	2	13.0 hp	10" x 5" dia.	24 lbs	Benson Mfg. Company (1002-B Std. blowers)
H_2O/Air Heat Exchangers	2		4" x 4" x 4"	3 lbs	HSD (special design)
Evaporator	1		6" x 6" x 6"	8 lbs	HSD
Refrigeration Unit (water-cooled)	1	3.9 hp	32 x 23 x 14"	247 lbs	Carrier (Model 6D41)
Chamber Circulation Fans	2	.134 hp	5" x 5" x 3"	2.5 lbs	Torrington Company (STA-410 series)
H_2O Pump and Motor	1	.33 hp	14" x 6" dia.	22 lbs	Eastern Industries
Air Filter	1		10" x 4" dia.	6 lbs	Filterite Corp. (Model A7)
Total (Components)		30.5 hp		376 lbs	

FIGURE 29

e. Power Supplies and Electrical Considerations

1. General and Summary

The ECS unit requires shaft power, and the electric lights and controls will use a certain amount of electrical power. In addition, heating requirements may be best satisfied with electrical units. Because the chamber may not always be located near a source of adequate electrical power, the study included consideration of a self-powered system for closed-loop operation with an eight-hour duty cycle. The results of the latter indicated a prohibitively heavy and expensive battery installation, hardly portable.

It must be realized, therefore, that self-power may be provided only with the following limitations:

1. Self-power must be obtained from a fuel-burning, energy-converting unit such as an internal-combustion engine, turbine or fuel cells operating to generate electrical power for the required duty cycle(s).

OR

2. Self-power operation must be limited to a much shorter duty cycle, an ECS output of less temperature control ability, or both. This duty cycle would be viewed as an emergency or temporary source of power until other power became available.

AND, IN EITHER CASE,

3. Open-loop operation on stored energy seems presently infeasible.

2. Potential Power Sources

a. The following types of self-power "cells" are at least partially feasible:

1. Storage batteries (all types)
2. Fuel-burning engines or turbines.
3. Other fuel-burning energy conversion systems.
4. Fuel cells.
5. Nuclear devices.

At present, #2 seems most practical, or #1 for short duty cycles.

b. The following types of outside power will be available at various locations: (Fixed facilities, auxiliary power units, aircraft, ship or truck electrical take-off power)

1. 115/220 VAC, 60 cps.
2. 115/220 VAC, 400 cps
3. 28 VAC, 400 cps.
4. 28 VDC
5. 12 VDC
6. 6 VDC

At present, #1 2, and 4 are the most likely to be available.

3. Use of Power

DC-operated devices perhaps are the best choice for all equipment. AC power can be transformed and rectified to appropriate voltages easily to operate DC devices; battery energy can then be directly applied without energy-wasting conversion devices.

The ECS might incorporate three separate input power connections:

1. 28 VDC
2. 28 VAC } selected frequency
3. 117 VAC }

4. Power Distribution Analysis (Closed Loop)

Closed loop. (Cooling Cycle)	Watts Required
1. Chamber fans	200
2. System flow fan	135
3. Freon Condensing unit	965
4. Two lamps @ 35 watt	70
	1370 W.

Closed loop. (Heating Cycle)	
1. System fan flow	131
2. Freon Condensing unit (Relative Humidity Control)	570
3. Heating unit	770
4. Two lamps @ 35 watt	70
	1541 W.

5. An Available Mobile Power Supply

A gasoline-driven, A.C. generator, rated at 1750 watts with a surge-wattage rating of 2170 is available. The output is 117 VAC 60 cycles and would require stepping-down and rectification to "tie" into the common power bus of the ECS. The gasoline-driven unit has a weight of approximately 86 lbs. (no fuel).

4 gal. of fuel = 26 lbs. (eight-hour supply)

The unit is available with and without electrical starting. Normal starting is by rope lanyard or recoil method. The physical dimensions are 21"x18"x18". A small increase in weight must be added for a battery and trickle charger in the event electrical starting is employed. The mobile power supply would be used only when the other power was not available or when power was needed in addition to other sources.

6. Storage Battery Analysis (Closed Loop)

A study from "Proceedings of the IRE" regarding battery development shows that even the best combination in an electrochemical secondary type battery would provide 300 watts for about 1 hour and the weight of the battery would be 48 lbs. The output would show rapid decay to complete discharge in approximately 75 minutes.

The requirement is (1540 watts) (8 hrs.) $\approx$ 12,300 whr = 12.3 kwh

To obtain this from a Nickel-Iron storage bank would require:

$$\frac{12{,}300 \text{ whr } (48 \text{ lbs.})}{(300) \text{ watts } (1) \text{ hr.}} = 1970 \text{ lbs.}$$

1970 lbs. of battery weight and the associated expense is prohibitive for most situations.

7. Other Electrical Requirements

1. - The electrical feed-thru shall be able to withstand the pressure differential.

2. - Brushless D.C. fans should be considered for their arcless commutation features.
This will reduce possible interference with communication and instrumentation systems.

One motor that might be considered is a NASA-developed fan motor used for item 102 in the LEM (Lunar Excursion Module) Life Support System. This motor runs at 13,000 RPM at 19.5 watts, 24 VDC, $\sim$ 24 oz. weight, 2 in.-oz. torque. The motor, if not completely appropriate, may possibly be modified to an acceptable configuration.

3. - The lamp globes should be implosion proof, extended into the chamber so that the pressure seal is made between globe and chamber, allowing bulb replacement from without.

4. - The sound-powered phones are very sensitive to noise, either acoustical or electro-magnetic, of any type. A consideration should be given to isolation from fan rotational noise (here it may be possible to choose a fan RPM above the response of the phones).

   Also, the positioning of any gasoline-powered generators should be remote to the external phone location for optimum communications.

2. Bio-instrumentation

The potential application of the bio-instrumentation researched for this study went beyond those applicable to portable, collapsible-type chambers. The most promising potential applications of the advanced instrumentation of this type lie with larger chambers utilized for research and hyperbaric oxygen therapy.

a. General Requirements

The bio-instrumentation selected should possess the following characteristics:

1. Unaffected by rapid changes of ambient pressure ranging from 1 to 6 atm. abs.;
2. Unaffected by rapid changes in temperature and humidity;
3. Resistant to shock and vibration;
4. Easily calibrated;
5. The sensor and wires of the system should produce minimal restriction upon patient movement and access to the patient.

b. Potential Applications to Small Decompression Chambers

The extent of physiologic monitoring instrumentation employed with these chambers would depend upon the physician in charge. Some of the most experienced Navy submarine medical officers feel quite strongly that no bio-instrumentation would be indicated, in that the changes in the patient are followed primarily by visual observation and voice communication. These two parameters do in fact represent the basis for the vast majority of patient monitoring. Others feel that additional monitoring of the vital signs would be indicated at time. For inclusion with the selected chamber designs, the following parameters and associated "hard wire" monitoring systems were selected as the probable maximum parameters and instrumentation complexity that would be desired in practice.

1.	Blood Pressure	-	A manual arm cuff/compensated sphygmometer for monitoring from inside chamber.
2.	Pulse Cardiac Rate	-	a) Digital palpation of peripheral pulse, or auscultation of heart with stethoscope for monitoring from inside. b) Hard wire EKG system as described in IV.A.1.a of Appendix VII, displayed on standard commercial oscilloscope, counted manually, for monitoring from outside.
3.	EKG	-	a) As immediately above--for monitoring from outside. Scope may be placed adjacent to observation port for interpretation by inside attendant.
4.	Respiratory Rate	-	a) Observe and count visually from inside and most of the time from outside.

b) Thermistor nasal clip with outside dial readout.

5. Body Temperature - a) Oral Thermistor (Yellow Springs or Hi-G) with outside readout if this parameter desired.

c. Potential Applications to Larger Chambers

Several other monitoring systems developed for the space program should be considered for further application to large hyperbaric chamber systems. We would point out the advantages of telemetered systems which reduce the accidental displacement of sensors attached to the patient. It is proper to note that NASA, via space program development contracts, has directly and indirectly been largely responsible for the accelerated development of these systems. Examples of these further applications are noted below:

1. The Mercury program bio-telemetry system for body temperature (rectal), EKG/cardiac rate, and respiratory rate.
2. Hamilton Standard EKG bio-telemetry system, derived from similar system developed under NASA contract
3. The previously mentioned electrodes developed by Day and Lippitt (MSC, NASA Houston).
4. The SRI temporal artery blood pressure transducer is intriguing, but still in the experimental stage.

Further discussion is included in Appendix VII.

V. REVIEW OF NASA SPONSORED AND OTHER SPACE RELATED TECHNOLOGIES UTILIZED IN THIS STUDY

Hyperbaric medicine and most NASA programs possess very similar basic requirements. A fundamental part of each is the support of human life exposed to unusual and often hostile environments. Both share the same basic philosophy which places maximum emphasis upon reliability and safety. In addition, portable hyperbaric chamber systems demand lightweight and compact size, two other requirements quite characteristic of space hardware. It is not surprising, then, to find technologic fallout from NASA sponsored programs to a field such as this.

Specific space related technologies utilized in this study are reviewed below.

1. Design of the Collapsible Convoluted Bellows

As previously noted, the possibility of applying this aspect of the Apollo Space Suit to small hyperbaric chambers initiated the overall study. Due to the higher pressure levels encountered in hyperbaric systems, direct transfer of components and exact techniques was neither expected nor accomplished. However, the experience gained during the development and fabrication of the Apollo suit was instrumental in enabling Hamilton Standard engineering personnel to develop the conceptual design of the convoluted bellows patient module.

2. Environmental Control Systems

The Lunar Excursion Module ECS and Apollo Space Suit Backpack contracts have given Hamilton Standard extensive and specific experience in the areas of compact atmospheric environmental control systems. This experience was employed throughout the analysis and conceptual development of both hyperbaric chamber ECS units as presented in this study. The following components, noted on pages 61 and 73, are directly related to this experience:

a. Closed Loop ECS

   1. CO_2 Removal Canister
   2. Evaporator

b. Open Loop ECS

   1. H_2O/Air Heat Exchangers
   2. Evaporator

It should be noted that additional space related components were investigated, but not utilized for these systems due to complexity and cost considerations.

3. Filament - Wound Fiberglass Fabrication

This method of fabrication was selected for the inner layer of the rigid hyperbaric chamber walls, having significant advantages as detailed in Section IV. United Technology Center, developer and fabricator of the 156 inch filament-wound fiberglass solid rocket motor casings, was the prime contributor of the fiberglass technology required for this design. We believe it is quite correct to state that the space program has been a major stimulus for the significant advances achieved in filament-wound glass technology during the past few years.

4. Bio-Instrumentation

The accelerated pace of achievement in physiologic monitoring in medicine today has closely paralleled the increased availability of new electronic and other devices developed under NASA sponsorship. With the portable chambers, we feel limited but significant use of cardiac monitoring, utilizing the advanced electrodes, transducers and other components developed for space programs, as well as nasal and ear mounted monitoring instrumentation would be employed by many physicians. The potential for more extensive application of space related bio-instrumentation in multi-man hyperbaric oxygen chambers is quite clear. The further use of bio-telemetry in chambers, as during surgical procedures, seems particularly advantageous.

APPENDIX I

WORKING SPECIFICATIONS FOR PORTABLE HYPERBARIC CHAMBERS

I SCOPE

This specification covers the design concept requirements for two versions of portable hyperbaric chambers in accordance with the Hamilton Standard Technical Proposal BST 6406. This work is being done in support of a contract issued by the Office of Technological Utilization, NASA, Washington, D. C.

Type 1 chamber consists of a two-man one-lock design; or a configuration which allows a patient on a stretcher plus an attendant, seated, to be contained within the chamber for periods up to 8 hours.

Type 2 is a two-man, two-lock chamber, with the locks detachable to thence become two (2) one-man chambers.

With both types of chambers, collapsibility and light weight for ease of transportation are essential. Also required for both types is a design employing an "open end" pressurizing system. It is expected that the only differences between the "open end" and "closed loop" systems will be differences in the external plumbing and pressurizing systems and not in the chamber itself.

In addition to the basic objectives listed above cost minimization is an important consideration. Additional requirements are listed in the following specification together with further details of the basic design.

II REQUIREMENTS

1. Structure

a. Sizes

Two designs shall be completed; type 1 and type 2. The basic envelope for each type shall be as minimal as possible consistent with internal minimum dimensional requirements.

b. Shapes

The shape of each chamber shall be such as to afford optimization of weight, envelope area, internal dimensions, structural stability and cost. The internal diameter of the area enclosing the prone patient shall be 24" ±1,

b. Shapes (Continued)

with an expanded area from the patient's middle thorax to the top of his head. The lateral width of the space in which the attendant sits shall be 30"; the fore and aft space dimensions shall be not less than 40" but shall be the subject of additional study and justification.

The diameter of the hatch through which the patient and the attendant enter the chamber shall be not less than 30" in diameter.

c. Weights

The weight of type 1 chamber shall not exceed 300 lbs. Type 2 chamber shall weigh only so much additional as necessary using the same approach to construction as the type 1 chamber. As a design objective, the type 1 chamber should weigh less than 300 lbs.

d. Portability

1. Both types of chambers are to be considered completely portable both in a collapsed and extended state; both with and without occupancy. Both types of chambers shall be designed to afford maximum collapsibility consistent with reasonable costs and other considerations. Further, the method of collapsing or extending the chamber shall be such as to not require tools or mechanical knowledge and shall be achievable with not more than two men of ordinary stature.

2. There shall also be provided a means of easily installing a stretcher with the patient into the extended chamber prior to pressurization.

3. Since the purpose of the chamber is for temporary use and for transporting patients from the scene of the onslaught of medical problems to a chamber where proper facilities are available, or for use by patients after having treatment in a large chamber, consideration shall be given in the design to the mating of these chambers to other chambers and their hatches.

2. Functional Performance

a. Pressure

Depending upon the final results of the engineering studies required to answer these requirements, two designs of chambers for each type may be considered. In the event that the second design is closely akin, similar, or of little difference in cost to the first, it shall be omitted.

1. High Pressure Design

For treatment of diving sickness, the chamber shall be capable of being pressurized to 6 atmospheres absolute as regular operating level.

2. Low Pressure Design

For treatment of less severe diving sickness and for other medicinal purposes, a design capable of withstanding 4 atmospheres absolute is sufficient for some applications.

b. Pressure Recovery

The chamber will have no air locks except for the medicant pass thru section which is, therefore, necessary to have fast pressurization capability and recovery for the slight loss involved when operating the medicant pass thru devices. A reasonable rating shall be determined, but as a design objective, a normal pressurization rate of 1 atmosphere per minute shall be achieved.

c. Flow Patterns

The chamber shall be designed so that air entering the chamber will automatically purge the chamber of accumulated CO_2 and other gas contaminants. The flow of air should not impinge upon either the patient or the attendant and should generally be unobtrusive and free of noise. If noise is present, suitable mufflers should be considered in the design.

d. Air Treatment

Air entering the chamber should be reasonably free (to hospital standards) of contaminants normally produced in air compressing systems such as excess water vapor and oil

d. Air Treatment (Continued)

vapor. A filter is required which can be easily changed from inside the chamber, the filter element being capable of being installed through the medicant pass thru.

e. Air Pressurizing Equipment and Power Supply

Lightweight portable air compressor equipment driven by 12 volts DC motors shall be provided. In addition, a means of operating the equipment from 117 volts 60 cycles shall also be provided together with means of supplying, from either source, 117 volts AC at 60 cycles to the interior of the chamber.

f. Pressure Control and Relief

The rate of pressurization shall be adjustable from 2 lbs per minute change of pressure to maximum recovery rate. In addition there shall be a pressure regulator capable of establishing any pressure in the chamber from 1 atmosphere to maximum within an adjustability and readability of ± 2 psi. There shall also be a safety valve which shall be manually adjustable and lockable to operate in the range of 2-6 atmospheres.

3. Accessory Features

a. Viewing Ports

Desirably there should be two view ports, one over the chest of the patient and one near the forehead of the patient. Recognizing, however, that the flexible portion of the chamber may not accommodate transparent sections, a single viewing port not less than 6" in diameter shall be provided in the region of the patient's head.

b. Medicant Pass Thru Lock and Shelf

A pass thru lock shall be provided approximately directly in front of the chest of the attendant. The lock shall be large enough to accommodate a one quart urine bottle. The lock shall have quick means of opening and closing.

c. Quick Operating Hatch

The chamber shall be equipped with a hatch cover capable of being opened within one minute without tools and by

c. Quick Operating Hatch (Continued)

one man either inside or outside the chamber.

d. Lighting and Power

There shall be at least one 35 watt incandescent bulb inside the chamber. In addition, there shall be at least one receptacle for plugging in a 117 volt 60 cycle appliance drawing not over 150 watts. The lighting fixture and power receptacle shall be explosion proof. The light fixture should be located in the chamber so as to afford the ability of the patient to read, the ability of the attendant to examine the patient, and the ability to illuminate the interior without producing a glare in either the patient's or the attendant's eyes.

e. Other Instrumentation

There shall be the following instruments outside of the chamber:

1. Pressure in chamber
2. Internal temperature
3. Clock with sweep second hand (mechanically wound and operated).

Inside the chamber there shall also be a pressure indicator, a clock, temperature gauge and an emergency flashlight.

f. Communications

The chamber shall be equipped with sound power telephones to communicate from inside the chamber to outside the chamber.

g. Electrical Feed-Thru

Feed thru devices shall be included in the design of the chamber for the following types of circuits:

1. 2 conductors insulated for 400 volts AC capable of passing 2 amps each.

2. 6 shielded leads and connectors for instrumentation, making a total of 12 electrical conductors.

h. Oxygen Connections

It shall be possible to attach externally to the chamber a valve of O_2 at high pressure. The chamber shall incorporate internally a pressure regulator and connections suitable for attaching an O_2 mask.

i. Hoisting Provisions

Both types of chambers shall include suitable hoisting hooks for lifting the chamber by crane in either a collapsed or extended state, with or without occupants.

III QUALITY REQUIREMENTS

1. Operative Cycles

The chamber shall be designed so that it can be collapsed and extended at least 500 times before repair or replacement of parts is needed. Along with this requirement, the chamber shall be capable of being pressurized and depressurized its full rating for the same number of cycles.

2. Environmental Requirements

a. Temperature

The chamber shall be capable of being operated at extreme ranges of temperatures from -20 to +140 and capable of being stored at temperatures from -40 to +150.

Equipment shall be designed or specified to cool air inside the chamber to a level not over 80°F whenever this may be necessary.

b. Humidity -

A relative humidity environment of 0-100% shall be accommodated. It may be necessary to include in the environmental control system means for reducing internal relative humidity to less than 70%.

c. Water and Salt Spray

The unit shall be capable of being operated on shipboard, on beaches, and in such other exposed places where ordinarily extremes of weather prevail. In particular, the unit should not be susceptible to excessive rates of deterioration from

c. Water and Salt Spray (Continued)

exposure to heavy rain storms or salt water (sea water).

d. Sand and Dust

Suitable resistance to sand and dust contamination shall be insured and the degree specified in details of a standard specification.

e. Fungus

Resistance to fungus growth and attack shall also be on the same basis as (d).

f. Shock and Vibration

The unit shall withstand normal shocks and vibration as might be experienced in transporting unit over rough roads by truck or in rough air by airplane: again according to standard specification as in (d).

g. Accidental Abrasion

The design shall consider the event of accidental abrasion through accidental bumping of any surface of the unit against other objects. Our particular concern is the flexible extensible portions of the structure and the various controls and instrumentation hardware which may protrude from the external surface of the unit.

3. Pressurizing Requirements

In designing the pressurized container, the requirements of the ASME code where applicable are followed for unfired pressure vessels.

4. Electrical Requirements

All electrical connections and wiring shall be in accordance with practices approvable by Underwriter's Laboratory or a suitable equivalent standard.

5. Leakage Allowances

In designing the pressurized container, its fittings, and its compressor system, consideration shall be given to a reasonable leakage allowance and this shall be included in the design consideration for the entire unit.

IV OPERATING AND MAINTENANCE REQUIREMENTS

1. Cleaning

The entire interior of the chamber shall be cleanable with standard hospital cleaning procedures which employ the use of soap, water and detergents. In addition, wiping with alcohol and formalin solutions will be employed.

2. Repairs to Flexible Elements

If the flexible portions of the chamber are determined to have any limitations on "life", consideration shall be given in the design to easing the task of repairing and replacing the flexible elements with a minimum of tools, equipment and shop facilities, as this may have to be done in the field at remote locations.

3. Manuals

The following manuals shall be provided as part of the design:

a. Operating - Mechanical

This manual shall describe all procedures necessary to operate the chamber in any of its various modes and shall include identification of all significant parts and components for each type of chamber and system.

b. Operating - Medical

This manual shall be written by a physician knowledgeable in the treatment of bends and other medical conditions for which the chamber might be employed. The manual shall assume that the reader has only a very limited medical knowledge, and that it will only be used in emergency situations where proper medical professionals are not available.

c. Maintenance and Repair: Testing

This manual shall include all necessary procedures for maintaining and repairing the chamber or any of its parts and accessories including overhaul instructions. The manual shall also include a description of tests which can be carried out to assure proper operation of the entire chamber and its systems.

4. Markings and Labels

All controls, instruments, and components of the chamber shall be suitably labeled with markings made by etching on a plastic material and thoroughly and reliably attached to the chamber.

APPENDIX II

I. CRITICAL BENDING MOMENT CALCULATION

(For determining the relative stiffness of different materials used in the construction of the attendant chamber.)

From Roark, IIId Edition:

Table XVI, Case N, thin-walled circular tube under a transverse bending moment,

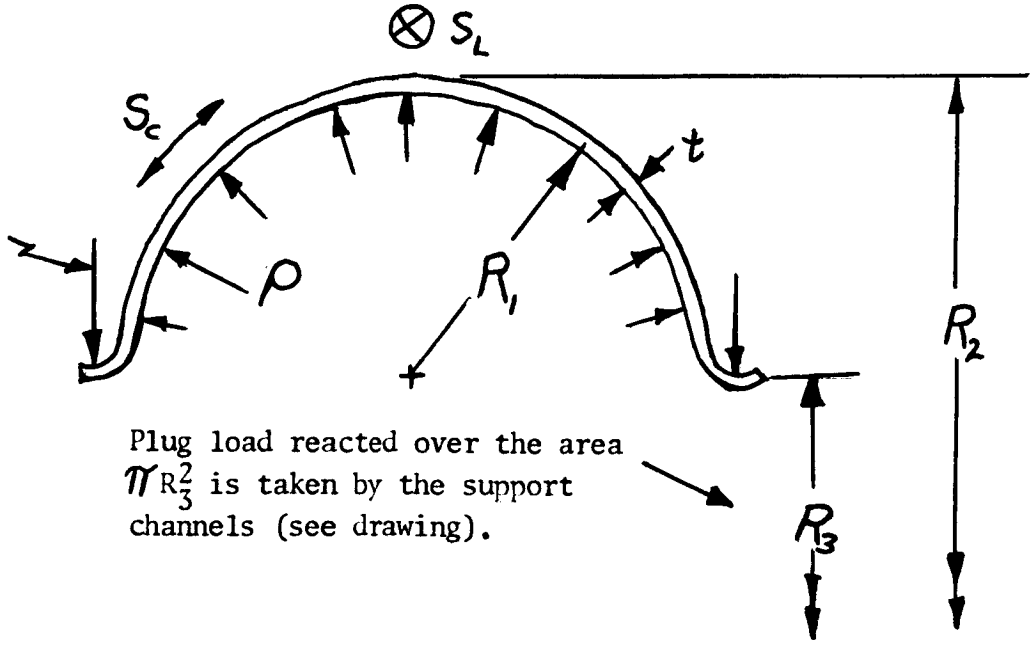
$$M' = K \frac{E}{1-\nu^2} \gamma t^2$$

The critical bending moment, M'_F, for a fiberglass cylinder, of an accumulative wall thickness of 5/32 inch, is 75 per cent of the critical bending moment, M'_S, of a steel cylinder of 0.081 thickness:

$$M'_F = \frac{E_F}{E_S} \times \frac{t_F^2}{t_S^2} \times M'_S$$

$$M'_F = \frac{6 \times 10^6}{30 \times 10^6} \times \frac{(0.156)^2}{(0.081)^2} \times M'_S = 0.75\, M'_S$$

II. STRESS IN THE FABRIC CONVOLUTIONS OF THE PATIENT CHAMBER MODULE (SVSK-62524)



Plug load reacted over the area πR_3^2 is taken by the support channels (see drawing).

S_C = Circumferential Stress, psi
S_L = Longitudinal Stress (into paper) psi
P = Maximum Operating Pressure (90 psig)
R_1 = Radius of Convolution Cross-Section, one inch
R_2 = Radius of Convolution O.D., 13.5 inches
R_3 = Radius of Convolution I.D., 12.5 inches

According to Timosheniso, Vol. II, Strength of Materials, "Thin Walled Vessels Submitted To Internal Pressure," radial equilibrium requires:

$$\frac{S_c}{R_1} + \frac{S_L}{R_2} = \frac{P}{t}$$

or, in terms of load per unit material width (N):

1) $$\frac{N_c}{R_1} + \frac{N_L}{R_2} = P$$

Examination of the structure reveals that:

$$N_C = \frac{P\pi(R_2^2 - R_3^2)}{2\pi R_2} = \frac{P(R_2^2 - R_3^2)}{2R_2} = 87 \frac{LB}{IN.}$$

From equation 1):

$$N_L = 45 \text{ LB/IN.}$$

These results are confirmed by applicable equations involving stress in a torus, also found in Timoshenko, Vol. II.

III. STRESS IN THE CONVOLUTION SUPPORT RINGS (SVSK-62524)

From Roark, IIId Edition:

Table XIII, Thick Vessels (case 27)

Maximum stress is the circumferential stress, S_2:

1) $$S_2 = P\left(\frac{b^2 + a^2}{b^2 - a^2}\right.$$

a = Internal Ring Radius, 12.5 inches
b = External Ring Radius, 14.0 inches
P = Pressure acting uniformly over internal ring surface, psi. (not operating pressure).

Since each ring supports the outward (radial) load incurred by half of each adjacent convolution,

$$P = \frac{\text{MAX OPERATING PRESSURE X PROJECTED CONVOLUTION AREA}}{\text{PROJECTED RING AREA}}$$

P = 1440 lb/in^2, and substituting in equation 1):

$S_2 = 12,700$ psi, MAX.

APPENDIX III

EVALUATION OF 22-INCH DIAMETER GEODESIC OVALOID FILAMENT-WOUND BOTTLE

Filament Winding Section, 3220

Solid Rocket Branch

31 January 1964

Prepared by:

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Approved:

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A

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EVALUATION OF 22-IN.-DIAMETER GEODESIC OVALOID FILAMENT-WOUND BOTTLE

A program was undertaken in which a test version of a motor case having an oblate spheroid configuration was fabricated and tested. The 22-in.-diameter bottle was fabricated of filament-wound fiberglass using the high-strength S-994 glass filaments. The case burst at 775 psig at a glass stress of 372,000 psi. Fiberglass composite weight was 3.71 lb. Figure 1 shows the dimensions of the ovaloid test bottle.

The case was 21.8-in. ID and 14.4-in. long. It was fabricated from S-HTS Owens Corning Fiberglass 12-end roving, using Union Carbide Bakelite ERL-2256 epoxy resin and MPDA hardener, and was cured with heat lamps at 350°F for four hours. The casing had a 0.6-in. cylindrical length and ovaloid end domes whose contour was derived by a computer program such that the theoretical fiber stress is constant at all points on the dome.

The mandrel was fabricated on a steel shaft using a plywood substructure. Metal screen was placed over the plywood as a base for Ultracal tooling plaster. The base coat of Ultracal was covered with a thin layer of washout plaster which was swept to the proper contour.

The helical windings were wound at 21°, which was slightly higher than the design winding angle of 16.6°. The tank was wound at the higher angle to give a single-segment winding pattern, which was considered advantageous over a multisegment pattern. Table I shows the ovaloid design factors.

TABLE I

OVALOID DESIGN FACTORS

Case dimension, OD	22.000 in.
Case dimension, ID	21.808 in.
Wall thickness	0.051 in.
MEOP (maximum effective operating pressure)	441 psia
Burst pressure	551 psig
Glass stress at burst	300,000 psi

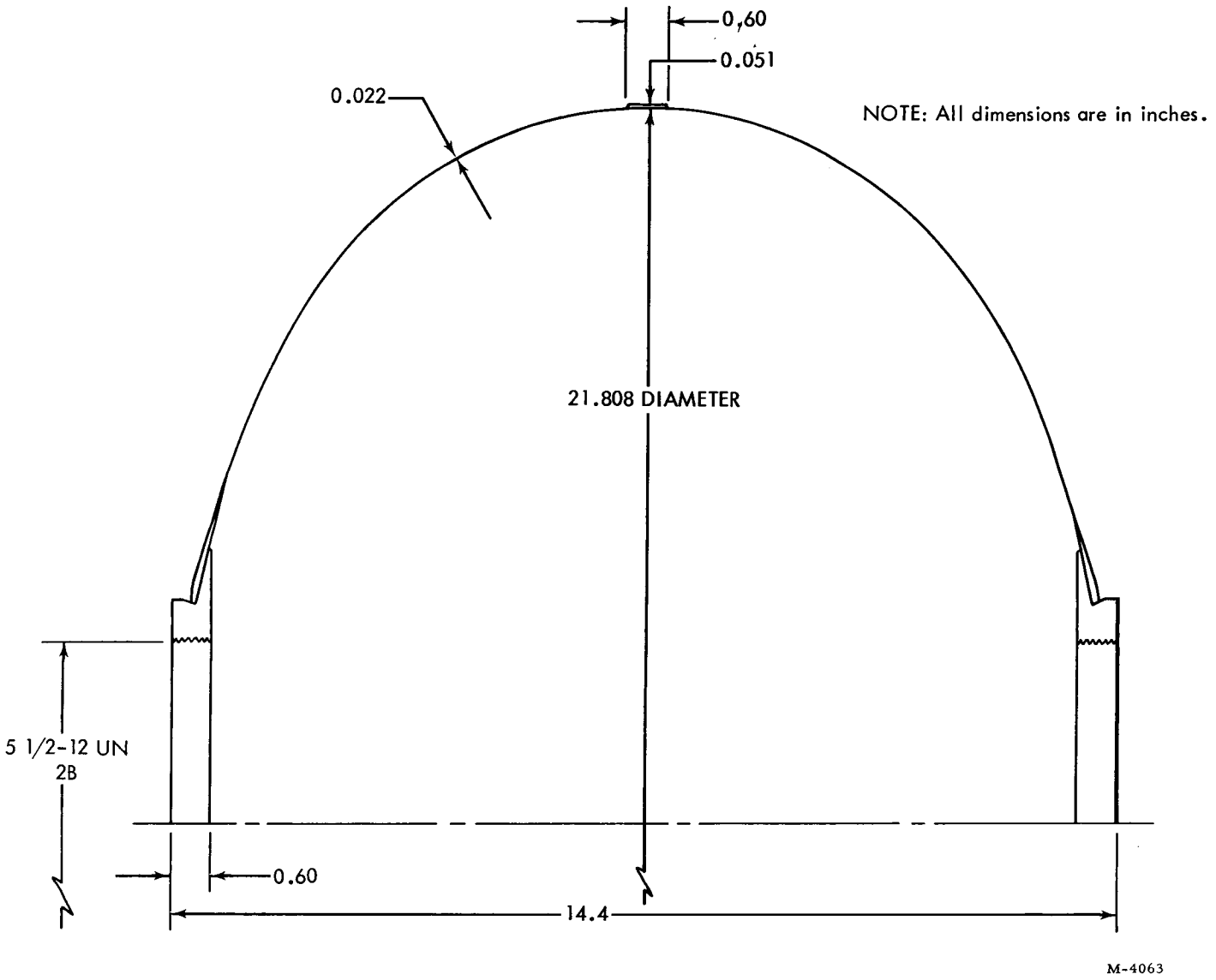


Figure 1. Ovaloid Test Bottle Dimensions

The design winding angle is

$$\alpha = \sin^{-1} \frac{R_E}{R_\alpha} = \sin^{-1} \frac{3.13}{10.965} = 16.59°$$

The helical glass thickness is

$$t_{\alpha G} = \frac{PR}{2\sigma_G \cos^2 \alpha} = 0.011 \text{ in.}$$

The hoop glass thickness is

$$t_{\theta G} = \frac{PR}{\sigma_G} \left(1 - \frac{TAN^2 \alpha}{2}\right) = 0.0194 \text{ in.}$$

The approximate wall thickness:

$$K_\alpha = 2.0 \text{ (helical resin factor)}$$

$$K_\theta = 1.5 \text{ (hoop resin factor)}$$

$$t_w = t_{\alpha G} K_\alpha + t_{\theta G} K_\theta = 0.051 \text{ in.}$$

The composite wall stress is

$$\sigma_w = \frac{PR}{t_w} = 119,000 \text{ psi}$$

The hoop strain at burst is

$$\epsilon = \frac{\sigma_G}{E} = \frac{300,000}{12.3 \times 10^6} = 0.0357 \text{ in./in.}$$

The case instrumentation consisted of one hoop extensometer, three longitudinal extensometers, and one pressure gage. The hoop expansion was measured by reading, with a dial indicator, the displacement of one end of a fine wire which was wrapped one turn around the case and tied to the opposite side of the test fixture from the dial indicator. The longitudinal extensometers were dial indicators pressing against the upper hydrotest closure plate and spaced at 120° intervals. These gages were to measure longitudinal growth and polar flange parallelism during pressurization.

The lower hydrotest closure plate was fastened firmly to the test fixture. All gages were read visually by telescope at approximately 50 psi intervals up to 550 psi, and the data are tabulated in table II. The pressurization followed the curve of figure 2, which shows the stops necessary for reading the gages.

TABLE II

DIAL INDICATOR READINGS FOR THE GAGES ON THE OVALOID TANK

Pressure	Hoop Gage	Gage No. 1	Gage No. 2	Gage No. 3
0	0.0	0.0	0.0	0.0
64	0.0	0.035	0.035	0.035
130	0.005	0.025	0.025	0.025
200	0.087	-0.020	-0.020	-0.020
277	0.247	-0.030	-0.025	-0.015
355	0.428	-0.040	-0.025	-0.017
400	0.535	-0.040	-0.025	-0.017
453	0.656	-0.030	-0.025	-0.017
500	0.778	-0.019	-0.022	-0.014
550	0.880	-0.008	-0.005	0.002

Figure 3 shows the actual and theoretical strain from the hoop extensometer. It will be noted that the strain rate is almost constant for theoretical and actual values. There is a 0.0075 in./in. strain lag in the actual to theoretical strain. This lag is caused by initial lag in the extensometer wire and pretensioning of glass created from wrapping tension. The lower slope of the actual curve is probably caused by the low modulus resin giving way slightly so that the composite modulus is lower than the glass modulus.

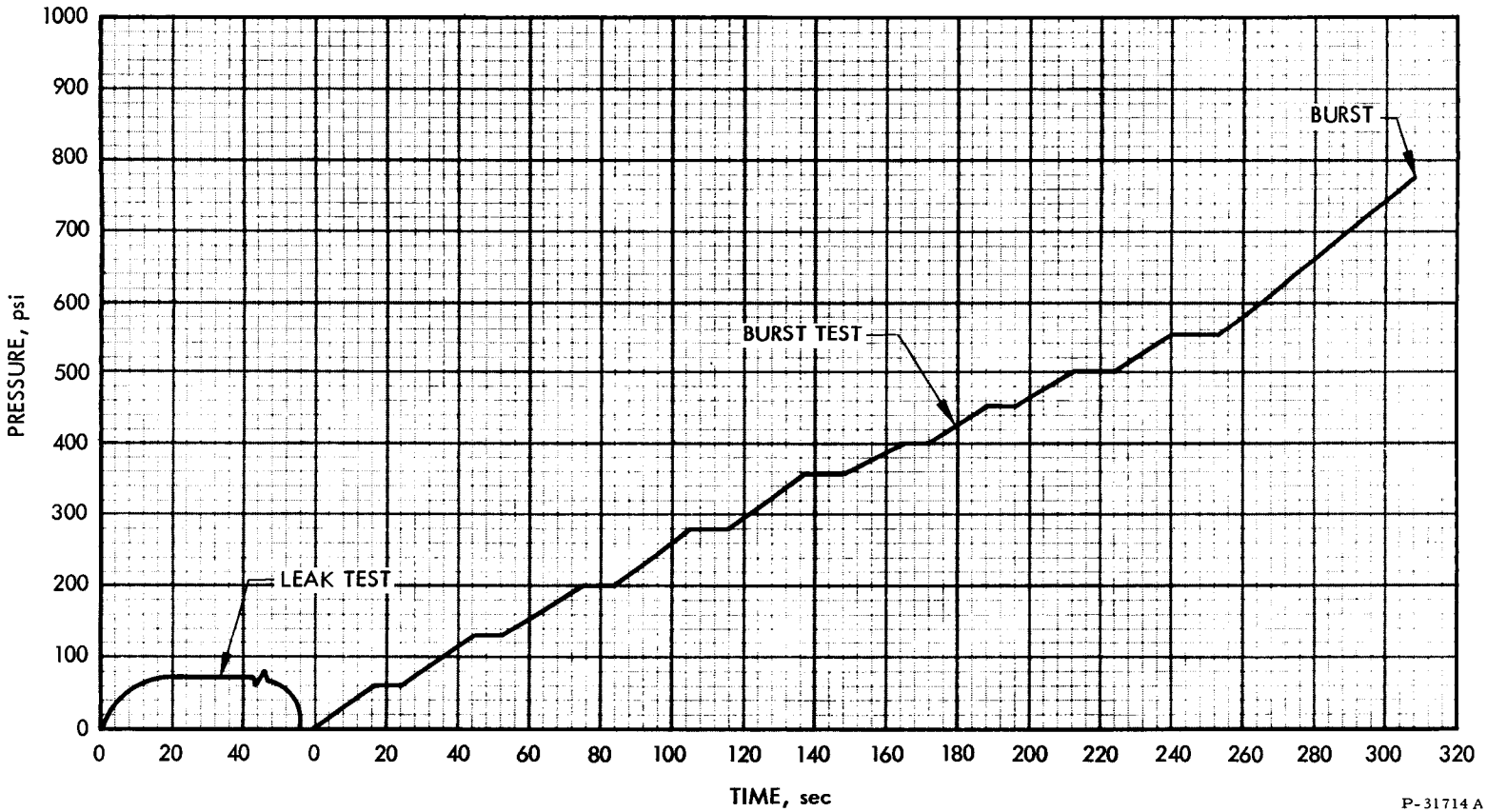


Figure 2. Pressurization Curve

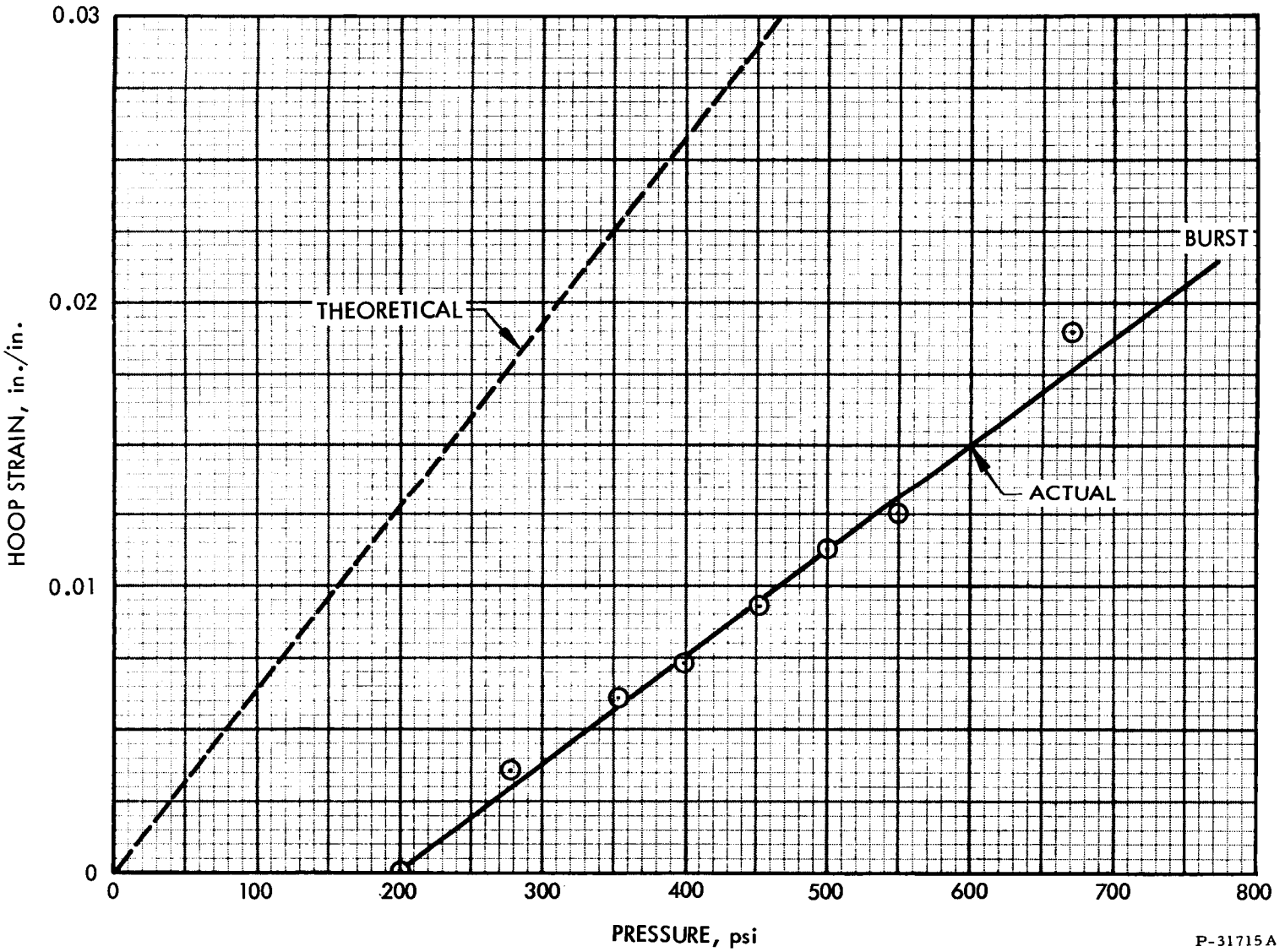


Figure 3. Hoop Strain versus Chamber Pressure

The data received from the longitudinal extensometers are vague but indicate that the adapter faces are holding parallel at low pressures. The maximum difference shown on the gages is 0.023 in. This gives an angle of rotation of approximately 3°.

The negative growth in length was not anticipated, and the instrumentation setup could not be considered reliable in this direction. Indications are that parallelism will be no problem, since true alignment was maintained up to the point of negative growth, as shown in figure 4.

Four samples were taken from the case, and the resin was burned out to determine the percentage of glass weight. The average of the four samples gave a glass weight of 67.8 percent of the composite. The theoretical glass weight determined from the glass volume is 60.8 percent of the composite.

The composite glass density in the cylinder was 0.068 $lb/in.^3$, and the composite density in the domes was 0.064 $lb/in.^3$

The burst data are presented below:

P_B = 775 psi (burst pressure)

σ_G = 372,000 psi (glass stress)

W_G = 3.7 lb (total glass composite weight).

The failure appeared to originate 4 in. below the polar opening in the dome section of the bottle, which probably indicates that the general configuration of the bottle is optimum.

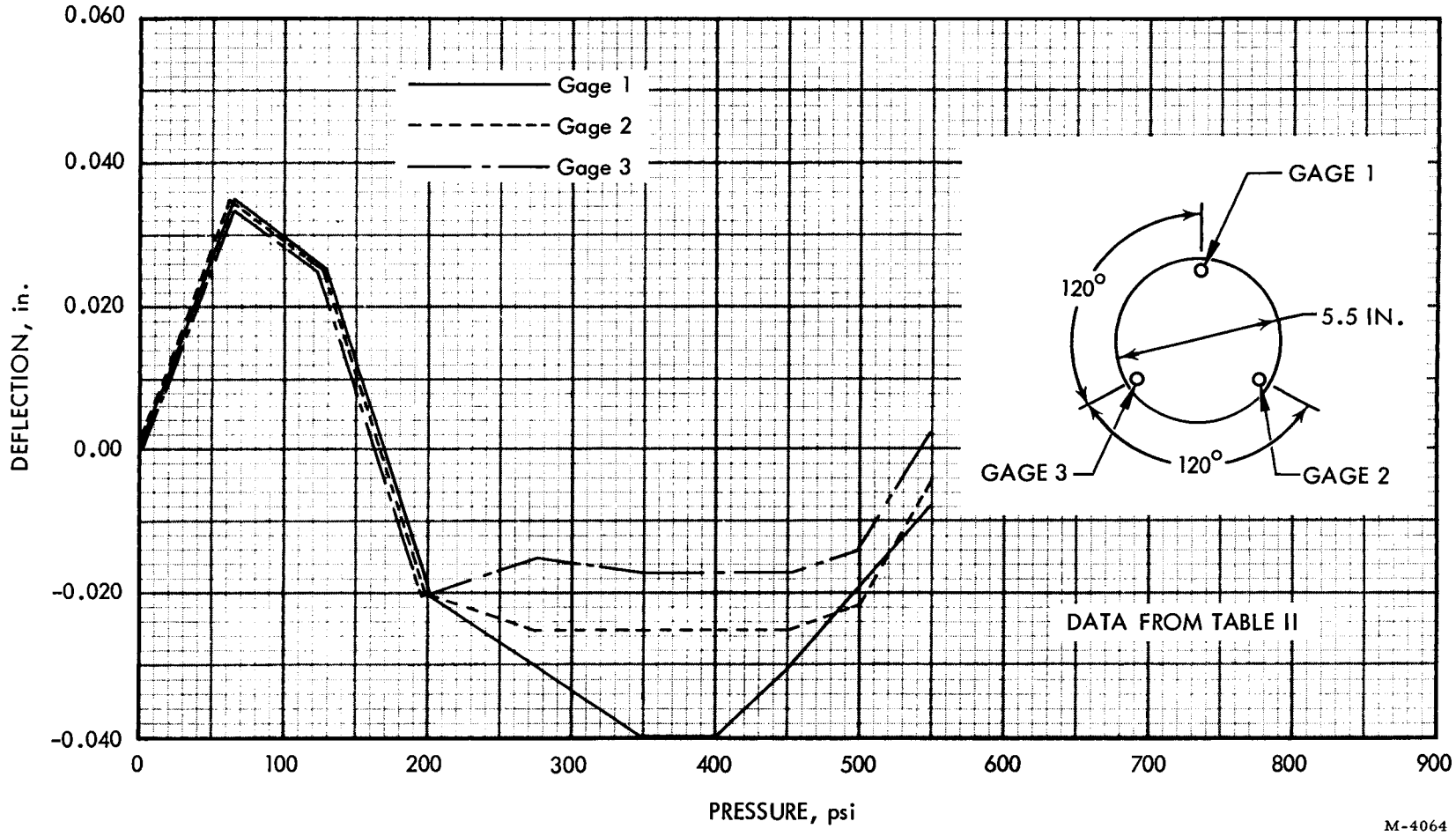


Figure 4. Longitudinal Growth versus Chamber Pressure

APPENDIX IV

SAMPLE CALCULATIONS

The analysis of the hyperbaric air loop is based on the fact that certain inlet conditions of temperature, absolute humidity, and air flow must be maintained. The conditions are:

T_{IN} = 55°F.

AH = .00144 lb. H_2O/lb air

$\dot{W}_{AIR}$ = 270 lbs/hr.

First Compressor:

$T_{IN} = T_{AMBIENT}$

$T_{OUT} = T_{IN} + \frac{(PR^{.286} - 1)}{\eta} T_{IN}$ $\qquad T_{IN}$ = °R

$PR = P_{OUT}/P_{IN}$

η is assumed to be 0.60

$T_{COMP} = T_{OUT} - T_{IN}$

COMP. HP = $\dot{W}C_P \Delta T_{COMP.} \times 3.93\ (10^{-4})$

First Intercooler:

$T_{IN(HX)} = T_{OUT}$ (COMP.)

E_{HX} is assumed to be .85

$E_{HX} = .85 = \frac{T_{H_{IN}} - T_{H_{OUT}}}{T_{H_{IN}} - T_{C_{IN}}}$

Assumed $T_{C_{IN}}$ to be 90°F.

$T_{H_{OUT}} = T_{H_{IN}} - .85(T_{H_{IN}} - T_{C_{IN}})$

$Q_{HX} = WC_p\ (T_{IN} - T_{OUT})$ AIR

Now a similar analysis was done for the second compressor and heat exchanger.

At this point we know the inlet conditions to the evaporator of the refrigeration unit. Since our outlet conditions to the evaporator are dictated by the desired chamber conditions we find the required capacity of the refrigeration unit:

$$Q_S = (\dot{W} C_P \Delta T)_{AIR}$$

$$Q_L = (\Delta H_{IN} - \Delta H_{OUT})\, W_{AIR} \times h_{fg}$$

Capacity Required = $Q_S + Q_L$

For the water loops of the system a simple analysis is as follows:

$\dot{W}_{H_2O}$ = 240 lbs/hr.

$$\text{pump power required} = \frac{\dot{W} \Delta P}{P \eta_o} \times \text{CONSTANT}$$

$$Q_{H_2O} = Q_{AIR} = (\dot{W} C_P \Delta T)_{H_2O}$$

HX's were then sized to have the appropriate capacities for cooling. HSD Technology was utilized.

Analysis of chamber heat transfer characteristics includes consideration of heat leak into and out of the chamber, the heat input by the two 100-watt fans and the heat carried away from the two men by convection.

A curve of heat vs flow rate for various ambient temperatures was generated by utilizing the following relationship.

$$Q_{LEAK} = UA\,(T_{AMB} - T_{AVG})$$

$$\frac{1}{UA} = \frac{1}{.1268_W 0.8 + .06625}$$

Resulting from:

$$\frac{1}{UA} = \frac{1}{H_{OUTSIDE} A_{OUTSIDE}} + \frac{1}{H_{INSIDE} A_{INSIDE}} + \frac{1}{\frac{K}{T} A_{MEAN}}$$

APPENDIX V

SAMPLE CALCULATIONS

Ambient Heat Leak

Outside film coefficient - turbulent flow across a tube

$$H_o = \frac{.025 \times G^{0.58} \times (1-.000576\ Ta)}{D^{0.42}}$$

G = lb/hr/ft^2 flow
Ta = of ambient temp.
D = diameter ft.

$$G^{0.58} = (10 \text{ mph} \times 5280 \times \frac{14.7 \times 144}{53.35 \times 600})^{.58} = 113.5$$

$$H_o = \frac{.025 \times 113.5 \times (1-.000576(140))}{(30/12)^{.42}} = 2.08 \text{ BTU/hrft}^2\text{°F}$$

at 140°F. ambient

Conduction Coefficient - 3/16" fibreglas K = 1.9 Btu/hr/ft^2°F/in.
1" plastic foam K = .14 Btu/hr/ft^2°F/in.

$$\frac{1}{K/t} = \frac{1}{.14/1} + \frac{1}{1.9/.1875} \longrightarrow K/t = .138$$

Inside film coefficient - turbulent flow in a round duct

Assume 5% area boundary layer, blockage by man

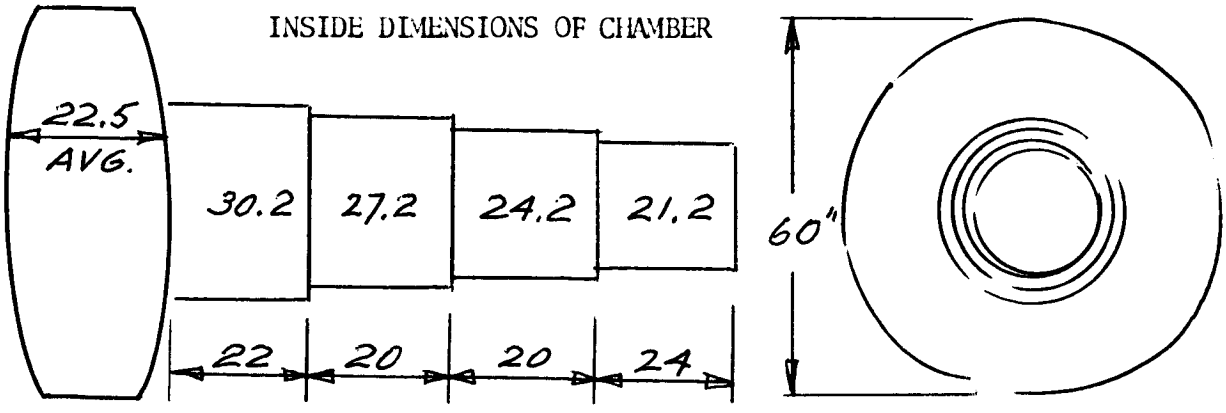
$$\text{Flow Area} = .95\left(\frac{\pi \times 28^2}{4 \times 144} - \frac{6 \times 24}{144}\right) = 3.7 \text{ ft.}^2$$

$$\text{Effective Diameter} = 12\sqrt{\frac{4 \times 3.7 \times 144}{\pi}} = 26"$$

$$R_E = \frac{WD}{A\mu g} = \frac{W \times 26}{3.7 \times 12 \times .0443} = 13.2\ W \quad (W = \text{lb/hr})$$

$$H_I = \frac{K}{D} \times .023 \times P_R^{0.3} \times R_E^{0.8} = \frac{.015 \times 12}{26} \times .023 \times (.709)^{0.3} \times 7.88\ W^{0.8}$$

$$H_I = .001132\ W^{0.8} \text{ BTU/hr/ft}^2\text{°F}$$



Area Inside = $\frac{\pi[(30.2x22)+(27.2x20)+(24.2x20)+(21.2x24)+(60x22.5)+(2x(30)^2-(15.1)^2]}{144}$

= 112 ft^2

Area Outside = $\frac{\pi[(32.5x22)+(29.5x20)+(26.5x20)+(23.5x24)+(62.6x24.8)+(2x(31.15)^2-16.25^2)]}{144}$

= 122 ft^2

Conduction Area = $\frac{112+122}{2}$ = 117 ft^2

Overall Heat Transfer Coefficient

$$\frac{1}{UA} = \frac{1}{h_I A_I} + \frac{1}{h_o A_o} + \frac{1}{K/t\ A_{cond}} = \frac{1}{112(.001132)W^{0.8}} + \frac{1}{122(2.08)} + \frac{1}{117(.138)}$$

$$UA = \frac{1}{.1268\ w^{0.8}} + .06625$$

For W = 507.5 UA = 8.35

Q leak = UA Δ T = 8.35 x (140-70) = 584 btu/hr.

FLOW THROUGH CHAMBER

$Wcp(T_{out} - T_{in})$ = Qmet sens. + Q leak amb. + Q fans

Qmet Latent = $2(.0655 + 700(.63 \times 10^{-4}))$ = .22 lb/hr H_2O

.22x1045 = 230 btu/hr

Qmet sens = 1400-230 = 1170 btu/hr

Qfans = 200 watt x 3.41 = 682 btu/hr

For T_{out} = 80 W - 507.5

(507.5) (.24) (80 - T_{in}) = 1170+584+682 = 2436

T_{in} = 60°

For Humidity Control

$W_{out} = W_{in} - \frac{.22}{W}$ 60°sat., = .001812 lb H 0

W out = .001812 - $\frac{.22}{507.5}$ = .002245 ⟶ R.H. = 62.5% 80°F

Carbon Dioxide Canister Sizing

LEM Suit Canister holds 5.4 lb LiOH, mesh size 4-8

apparent density = 31 lb/ft^3

Reported data for 4-8 mesh SODASORB (per J. Hopper, W.R. Grace Co.)

1350 gm. = 1500 ml. SODASORB + 705 ml. void

Apparent Density = $\frac{1350 \times 1000}{2205 \times 453.6 \times 0.353}$ = 38.3 lb/ft^3

Hamilton Standard
DIVISION OF UNITED AIRCRAFT CORPORATION

STUDY TO RELATE APOLLO SPACE SUIT TECHNOLOGY TO THE FIELD OF HYPERBARIC MEDICAL THERAPY

Prepared for

Office of Technology Utilization
National Aeronautics and Space Administration
Washington, D. C.

By

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25 March 1966

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I. INTRODUCTION

This study was performed to investigate the feasibility of applying technologies developed for the Space Program to the field of Hyperbaric Medicine. Originating with the thought of applying technologic advances developed for the Apollo Space Suit and Back Pack, which is in fact a portable self-contained pressure "chamber," it was also apparent that developments in other space related fields such as instrumentation and rocket casing fabrication offered additional potential applications to hyperbaric chamber systems.

Recognizing the many ramifications of Hyperbaric Medicine and its rapid growth within recent years, it was inherent to the study to select the area or areas most likely to benefit from space-oriented technologic advances. It was our opinion that the most logical areas to pursue would be those with a potential need for further application of components exhibiting the qualities of lightweight and compactness so characteristic of most space-oriented equipment. As a result, although the study was not restricted entirely to such areas, it has emphasized further development in the field of portable, collapsible hyperbaric chamber systems.

The greatest need and potential utilization of these compact hyperbaric chamber systems are in connection with diving and flying activities. As these operations continue to spread over wider geographic areas and as scuba diving for sport becomes more popular, space and transportation capabilities are requiring smaller size and lower weight. Hence, the conceptual designs presented in this report are primarily intended to fulfill the functions of routine decompression and treatment of decompression sickness. However, as Dr. Alvis has pointed out, to many people "a chamber is a chamber is a chamber," and it is probable that chambers of this type would also be utilized as hyperbaric oxygen chambers for the treatment of other pathology simply because they were available in a given area.

The results of this study present conceptual designs of two basic portable, collapsible hyperbaric chamber systems, embodying several variations of the subsystems involved. We feel these represent a reasonable basis for further development of specific hardware systems. In general, it has been the philosophy to include components offering the broadest capabilities but recognizing that individual systems would be less complex in some instances to meet specific needs. In many instances, we have been conservative in regard to various characteristics, attempting to meet the more extreme requirements rather than the less demanding requirements.

We would like to express our sincere appreciation to the many individuals in the fields of Hyperbaric Medicine, diving and aviation, who have given so willingly of their time to answer our many questions and helped provide us with a better understanding of the environment and needs of their activities. Our particular thanks to:

Harry Alvis, M.D., consultant on the study, and his staff:

Captain Robert Workman, Commander Hedgepeth, Captain Waite, Captain Mazzone and other personnel of the U. S. Navy; Captain Bruce Bassett, USAF(MC):

Ken Knott, Willie Meyers, Ed Wood, Chuck Adams and other divers; Ed Granle of Hyperion Constructors; Ray Wampler of the Pile Drivers Union, Wilmington, California;

Adams Cowley, M. D. and his staff at the University Hospital in Baltimore; Julius Jacobson, M. D., and Mr. May and staff at Mt. Sinai Hospital, New York City; Ivan Brown, M. D., Wirt Smith, M. D. and others at Duke University Hospital; E. Lamphier, M. D. and his staff in Buffalo; Carl Zenz, M. D. of Milwauki; and the many others who have contributed to this program.

It is our sincere hope and desire that this study will directly or indirectly stimulate further developments in the field of Hyperbaric Medicine and result in useful and significant contributions to the field.

II. SUMMARY AND CONCLUSIONS

A. General Summary

This study investigated the application of various NASA-sponsored space technologies to the field of Hyperbaric Medicine. The working environments and needs of military and civilian diving and aviation operations, and of hospital hyperbaric medical facilities, were investigated. Current domestic and foreign hyperbaric chamber systems were studied. These evaluations indicated a definite and apparently growing need for portable hyperbaric chamber systems, possessing a two-man capability whenever possible, in certain types of diving and possibly flying situations. This need is not adequately satisfied by present equipment. In addition, further application of NASA-sponsored bio-instrumentation to hyperbaric chambers of all sizes appeared desirable. Consequently, the study proceeded with the design of two portable, collapsible hyperbaric chamber system concepts, intended primarily for routine decompression and treatment of dysbarism associated with diving operations. They also possess the capability for limited use in hyperbaric oxygen therapy of other pathology.

Target engineering and medical specifications were compiled for the design and analysis work. Conceptual designs were completed for two types of portable, collapsible hyperbaric chamber systems:

1. A two-man, one-lock chamber incorporating foam-filled fiberglass sandwich and convoluted rubber-impregnated fabric construction.
2. A two-man, two-lock chamber, which is separable into two individual one-lock chambers without pressure loss of fiberglass sandwich.

Two scale models illustrating these chamber configurations were constructed as part of the study. In addition, comparative weight studies contrasting other fabrication materials, and contrasting rigid versus collapsible configurations were performed. Closed-loop and open-loop environmental control systems for these chambers were studied and two respective approaches proposed. A substantial portion of the closed-loop system was derived from the Apollo space suit environmental control system with appropriate modifications. A comparison of the two hyperbaric chamber systems is presented in the Summmary Table at the end of this section.

The need for extensive utilization of the more refined bio-instrumentation with these chambers in performing their primary function was found to be limited. Appropriate basic bio-instrumentation is proposed. The extent of such monitoring equipment would be determined by the physicians utilizing any given chamber. Other advanced bio-instrumentation for potential utilization in large chamber designs is reviewed.

B. Conclusions

1. There is definite and growing need for more compact and lightweight hyperbaric chamber systems in certain diving situations.
2. These chambers should provide room for an attendant with the patient whenever possible.

3. Current chamber systems do not satisfactorily meet this need.
4. Technologies developed for the space program can be effectively utilized to meet these requirements of reduced weight and size.
5. Analysis and conceptual design studies as presented indicate the feasibility of utilizing a number of these newer technologies.
6. In general, the weight and size requirements for hospital hyperbaric chamber systems do not justify the complexity and higher cost of collapsible chambers. However, certain features of fabrication, configuration, or equipment of the concepts presented may be desirable for hospital systems.
7. Additional development and testing directed toward prototype construction are indicated to demonstrate manufacturing feasibility of these concepts.

SUMMARY TABLE

		Two-Man One-Lock Chamber with Convoluted Bellows		Two-Man Two-Lock Chamber with Telescoping Sections	
		Patient Module	Attendant Module	Patient Module	Attendant Module
1.	Basic Fabrication Material	Nylon Fabric impregnated with silicone or latex rubber.	Filament wound fiberglass/ polyurethane foam sandwich.	Filament wound fiberglass/ polyurethane foam sandwich.	Same
2.	Module Weights	215 lbs	185 lbs.	300 lbs.	360 lbs.
3.	Total Chamber Weights	400 lbs		660 lbs	
4.	Closed Loop ECS Weight	110 lbs		110 lbs	
5.	Chamber Volumes	Approx. 31 $ft.^3$	Approx. 25 $ft.^3$	Approx. 20 $ft.^3$	Approx. 50 $ft.^3$
6.	Closed Loop ECS Volume	Approx. 6 $ft.^3$		Approx. 6 $ft.^3$	
7.	Patient Space	24"D x 75"l	----	26"D x 76"l	----
8.	Attendant Space	----	32"D x 61"h	----	5' x 5' x 2 1/2'w
9.	Clear size of Hatch Openings.	----	21"w x 33"h (ovoid)	25"w x 20"h (ovoid)	21"w x 33"h (ovoid)
10.	Chamber wil fit through door	34" wide		34" wide	
11.	Floor Space Req. for Storage (Minus ECS)	3' x 5' (5 1/2 ' high)		4' x 5 1/2' (5 1/2' high)	
12.	Pass Throughs	----	1(5 1/2"x11")	1(5 1/2"x6 1/2"av.)	1(5 1/2"x11").
13.	View Ports	3 (6"D)	2 (6"D)	4 (6"D)	2 (6"D)
14.	Operating Pressure Rating	6 Atmospheres Absolute		6 Atmospheres Absolute	
15.	Max. Rate of Pressurization	One Atmosphere/minute		One Atmosphere/minute	
16.	Internal Temperature Control Range	70°- 80° F.		70°-80° F.	
17.	Internal Humidity Control Range	30%- 75% R. H.		30%- 75% R. H.	
18.	Contaminate Control: Particulate	Mechanical Filter		Mechanical Filter	
	Carbon Dioxide	Soda-lime Cannister		Soda-lime Cannister	
19.	Air Sources	--Compressed Air Bottles or Ambient via Compressor---			
20.	Electrical Power Sources	--D. C. via Separate Generator, Transportation Vehicle Electrical System, or Batteries.			

III. DEFINITION OF OPERATIONAL AND SYSTEM REQUIREMENTS

A. Preliminary Surveys

1. Available Hyperbaric Chamber Systems

A thorough review and study was made of currently available hyperbaric chamber systems. This was accomplished by collecting and analyzing the literature published by the several manufacturers. In addition, some of these chamber systems were examined during visits to various facilities. Products of the following manufacturers were included in this phase:

1. The Bethlehem Corporation
   Bethlehem, Pennsylvania
2. Biggs-United, Division of
   United Sheet Metal Company, Inc.
   Akron, Ohio
3. Borg-Warner Corporation
   Des Plain, Illinois
4. Dixie Manufacturing Company
   Baltimore, Maryland
5. Dragenwerk, Germany
6. Roberto Galeazzi, Ltd.
   LaSpezia, Italy
7. Linde Division
   Union Carbide Corporation
   Tonawanda, New York
8. Normalaire, Ltd.
   Yeovil, England
9. Societe Spirotechnique
   Levallois, France
10. S.U.R.F. Enterprises
    Los Angeles, California
11. Vacudyne Corporation
    Chicago Heights, Illinois
12. Vickers Research Ltd.
    England

2. Hospital Facilities, Diving Facilities and Operations, and Aerospace Facilities

Personal visits and detailed discussions regarding equipment, needs and problems were accomplished at several of these facilities by both engineering and medical members of the study team. Without a doubt, this proved to be the most valuable and effective method of familiarization with the multiple facets of the working environments.

During the course of the study, the following facilities and personnel were visited:

1. Mt. Sinai Hospital, New York City
2. University Hospital, Baltimore, Maryland
3. Several civilian divers and construction personnel on site, Long Beach Harbor, California
4. A divers union representative, Wilmington, California
5. U.S. Navy Experimental Diving Unit, Washington, D. C.
6. U.S. Navy Submarine Base, Groton, Connecticut
7. USAFSAM Dysbarism Management Team Facility, San Antonio, Texas
8. Our own hyperbaric chamber at Windsor Locks, Connecticut

In addition, prior personal contacts with medical hyperbaric facilities and personnel at Duke University, New York State University at Buffalo, Aberdeen and Glasgow, Scotland, and The University of Pennsylvania assisted materially in providing a wider base of knowledge for the study.

B. Definition of Need and Functional Requirements

Based upon the results of the preceding studies and contacts, the areas of need and subsequent functional requirements were defined.

1. Definition of Need

The functional applications of hyperbaric chambers can be separated into two basic areas:

a. The treatment of multiple forms of pathology (other than dysbarism), including pulmonary, vascular, toxic and infectious diseases, traumatic injuries, and cancer. This form of therapy is based upon exposure to oxygen under pressure to produce a greatly elevated pO_2 within the body, and is nearly always provided at a hospital facility. The number of such hyperbaric oxygen facilities and subsequent utilization of HBO therapy is rapidly expanding.

b. The treatment of dysbarism (decompression sickness) and routine decompression associated with diving operations. These hyperbaric facilities are usually located at or near the diving site, or at military (Naval and Air Force) medical facilities. Either compressed air or oxygen may be used in the treatment of dysbarism.

In general, the relative weight and size restrictions for hospital hyperbaric facilities are not severe (speaking in terms of pounds, not tons, and similarly in regard to volume). The significant use of hyperbaric oxygen chambers in ambulances is still a very questionable area, at least in the United States. In addition, it is rare indeed that even a small hospital hyperbaric chamber need be lifted. The principal area of application of NASA-sponsored technologies to these systems appears to be in further application of the more advanced physiologic monitoring devices, with further consideration of lighter-weight, medium-size chambers certainly justified.

However, in terms of portability and collapsibility, the potential applications in the fields of diving and flying operations were sufficiently greater to justify concentrating the bulk of the study effort in this direction. We did not find that extreme lightness and compactness are necessary or even desirable for most chambers of this type. Several factors, however, are contributing to a significant increase in the need for less cumbersome chambers. Some of these factors are:

1. Wider geographic spread of commercial oil undersea drilling sites.
2. Ever-increasing military diving activities, often operating from a submarine, small boat, or aircraft.
3. The surprising increase in sport scuba diving.
4. To some extent, the wider use of overcompression for the treatment of "altitude bends."

Any of these may, and often do, involve operations some distance from a fixed or even transportable hyperbaric chamber facility. The need for a decompression facility on site is significant, particularly in severe cases of bends or aero-embolism, when even a short delay may result in permanent damage. Given a facility on site in some of the more remote areas, the additional capability of being portable for transportation and transfer of the patient into a larger chamber takes on additional significance. For these reasons, this area of hyperbaric medicine was selected for primary emphasis.

3. Definition of Functional Requirements

The functional requirements were defined by taking into consideration the intended purpose of the chamber, the personnel available to operate the chamber, and the environment in which it would be employed. Some of these requirements are:

1. Reliability

   Divers are basically conservative people, and it is our impression that they will go without many features in order to retain reliability.

2. Operating Pressure

   The standard U.S. Navy treatment tables were utilized to determine this parameter. It was the consensus that the newer oxygen tables supplement, but do not replace, the standard tables.

3. Two-Man Capability

   The need whenever possible for an attendant in the chamber was made loud and clear to us in our contacts with divers. The medical reasons for this are many and obvious. However, there are times when available load and space capacity of transportation vehicles preclude anything but a one-man

chamber. Hence, our design team pursued the two-man, two-lock concept, the locks being separable.

4. Ruggedness

   Even at the sacrifice of some added weight, it must stand up to abuse on a barge, boat or ship. In addition, it must resist salt water and petroleum products.

5. Stable

   Must be able to be lashed down. If wheels are used, they must lock.

6. Portability

   If at all possible, light enough to be "man carried."

7. Adequate ECS

   This may range from a very simple filter-compressor-valve system to the more complex "self-contained" system. For prolonged transportation, the latter is required. A maximum operational time of eight hours was recommended based upon expected transportation time via plane to a "mother" chamber if needed.

8. Cost

   A very significant factor, and very important in the case of the individual diver. Low cost is desirable, but a higher cost may be acceptable if the added features can justify it.

9. Adequate hatches, mating capability to a mother chamber, lighting, sound attenuation and communications are required.

C. Formulation of Study Performance Specification

After definition of the basic functional requirements, a tentative Performance Specification was drawn up (Appendix 1). This specification was used as a "target" set of requirements during the study.* The specification is believed to be reasonably realistic and practical. Some modifications would be expected, however, as the result of detailed design and testing beyond the conceptual design phase.

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* Additional specifications in regard to bio-instrumentation are included as an integral part of Section IV.E.2.

IV. PROPOSED DESIGNS

A. Concepts Considered

As noted above, in the early phases of the study, the functional requirements of these types of hyperbaric chambers were defined, following which the system performance specification was drawn up. As this specification was being evolved, various conceptual possibilities were examined. Figure 1 illustrates some of the concepts considered with certain pertinent facts about each concept. As illustrated in this Figure, four shapes were considered for the attendant module and, two forms of collapsibility were considered for the patient module for a total of eight basic concepts.

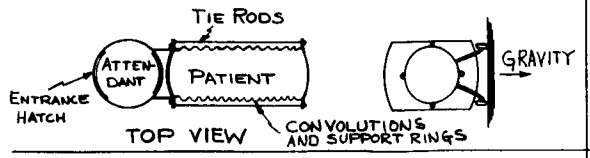
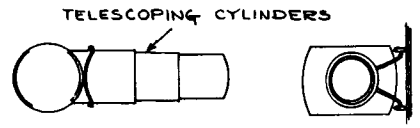
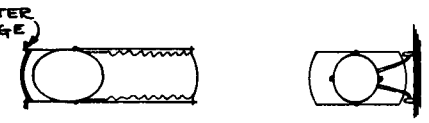
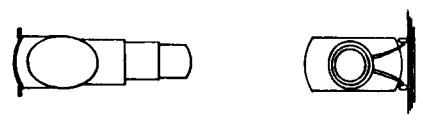
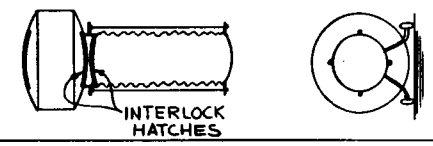
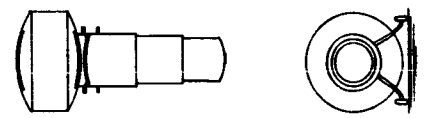
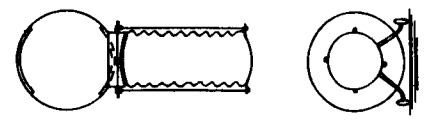
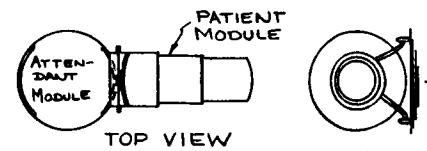
Concepts 2a and 3b were selected for further development; 2a representing the minimum practical envelope for a two-man, one-lock chamber, and 3b offering the greatest ease of collapsibility. Concept 2a requires some form of adapter flange to allow transfer of the patient under pressure to a mother chamber, whereas the detached patient module of 3b may be placed within a mother chamber, the latter then being pressurized and transfer executed.

Concept 2a was modified to have a cylindrical attendant module of 32 inches diameter as a result of full size cardboard mock-up studies which indicated adequacy of the cylinder from an envelope standpoint. The cylindrical shape, being a much more desirable pressure vessel shape than the ellipse, allows a significant weight saving (at 300 pounds saved).

Note that these two basic concepts represent in reality four potential concepts by interchange of attendant and patient module configurations as outlined below:

	Attendant Module	Patient Module	Functional Type
1. (Concept 2a)	Vertical Cylinder	Convoluted Bellows	Collapsible 2-man, 1-lock chamber.
2. (Concept 3b)	Section of Horizontal Cylinder	Telescoping rigid sections	Collapsible 2-man, 2-lock chamber, modules detachable.
3.	Vertical Cylinder	Telescoping rigid sections	Collapsible 2-man, 1-lock chamber.
4.	Section of Horizontal Cylinder	Convoluted Bellows	Collapsible 2-man, 2-lock chamber, modules detachable.

Further, concept 2a could be redesigned to incorporate a separable inter-lock to become a 2-lock chamber with the resultant increase in weight and overall length.

SCALE: APPROX. 1/50	CONCEPT	DESCRIPTION (ATTENDANT MODULE)	DESCRIPTION (PATIENT MODULE)	COLLAPSED (STORAGE) LENGTH	RELATIVE WEIGHT (1=LIGHTEST)	REMARKS -
	1A	$3\frac{1}{2}$ FT. I.D. X 5 FT. HIGH CYLINDER	$2\frac{1}{2}$ FT. I.D. X 7 FT. LONG (CONVOLUTIONS)	APPROX. 6 FEET	4	SEE NOTES 1 & 2 PATIENT MODULE MAY BE DETACHED AND PLACED INSIDE "MOTHER" CHAMBER WITHOUT DISTURBING PRESSURIZED ATMOSPHERES OF EITHER PATIENT OR ATTENDANT MODULES.
	1B	SAME AS ABOVE	$2\frac{1}{2}$ FT. I.D. (LARGEST SECTION) X 7 FT. LONG	APPROX. 5 FT.	3	
	2A	$2\frac{1}{2}$ FT WIDE X $3\frac{1}{2}$ FT LONG ELLIPSE (INSIDE) X 5 FT HIGH	2 FT. I.D. X $5\frac{1}{2}$ FT. LONG (CONVOLUTIONS)	5 FT.	2*	* WEIGHT BASED ON A 32 INCH I.D. CYLINDRICAL ATTENDANT MODULE WHICH WAS SUBSTITUTED FOR THE $2\frac{1}{2}$ X $3\frac{1}{2}$ FOOT ELLIPSE AFTER CARDBOARD FULL SIZE MOCK-UPS INDICATED THAT THE CYLINDER PROVIDES ADEQUATE ROOM FOR THE ATTENDANT. (ATTENDANT SITS AT THE HEAD OF THE PATIENT.) THIS CHAMBER MAY BE MATED TO THE "MOTHER" CHAMBER BY THE ADAPTER.
	2B	SAME AS ABOVE	2 FT. I.D. (LARGEST SECTION) X $5\frac{1}{2}$ FT. LONG	APPROX. 5 FT.	1*	SAME AS 2A
	3A	5 FT. DIA. CYLINDER ON SAME AXIS AS PATIENT MODULE	SAME AS 1A	APPROX. 5 FT.	6	INTERSECTION OF THE MODULES MAY BE OFFSET TO ALLOW MORE ROOM FOR THE ATTENDANT. ATTENDANT SITS AT THE SIDE OF THE PATIENT'S UPPER TORSO.
	3B	SAME AS ABOVE	SAME AS 1B	4 FT.	5	SAME AS 3A TELESCOPED PATIENT MODULE MAY BE STORED IN ATTENDANT MODULE
	4A	5 FT. DIA. SPHERE	SAME AS 1A	APPROX. 7 FT.	8	CONCEPT 4 WAS DISCOUNTED BECAUSE OF ITS EXCESSIVE ENVELOPE.
	4B	SAME AS ABOVE	SAME AS 1B	APPROX 6 FT.	7	

NOTES:
1- CONCEPTS 1, 3 AND 4 ARE TWO LOCK, DETACHABLE MODULES
2- CONCEPT 2 IS A ONE LOCK, NON-DETACHABLE CHAMBER WHICH WILL PASS THRU STANDARD DOORS.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ± ____ ANGLES ± ____. EXCEPT FOR DRILL END FORMS, FILLET RADII ____ TO ____ SURFACES HAVING A COMMON AXIS CONCENTRIC WITHIN ____ TIR. ____
BREAK EDGES .002-.025
△ MARK PART IDENTIFICATION: MIL-STD-130 PER HS333. DRAWING INTERPRETATION PER ____. CLEANING, PRESERVATION AND HANDLING PER HS1550-C ____ P ____. SURFACE CHARACTERISTICS PER ____

NEXT ASSY | USED ON | APPLICATION

INSPECT-TEST DESIGNATED AREA(S) PER | MATERIAL
DES | SPECIFICATION(S)
A | HARDNESS
B | HEAT TREAT SPEC
SURFACE COATING
MFG SPEC
ALL AREAS | MAKE FROM
PROD. CODE

DRAWN | CHECKED | DESIGN | DFTG | MAT'L | PROJ | COST | FCTY | Q & R
CONTRACT NUMBER
EXP MFG | PRELIM PROD. | PROD.

Hamilton Standard — TWO MAN PORTABLE - COLLAPSIBLE CHAMBERS DESIGN WORK SHEET

SIZE D | CODE IDENT NO. 73030 | SVSK-61918
SCALE: | WEIGHT: | LB | SHEET | OF

FIGURE 1

However, basic concepts 2a and 3b were selected for further design development to provide two integrated systems which would more clearly demonstrate the technologies involved.

B. Survey of Potential Materials

1. The following materials were considered:

   a. fiberglass
   b. wrought carbon and low alloy steel
   c. stainless steel
   d. aluminum
   e. titanium
   f. magnesium

2. Table I lists salient properties of above materials.

   a. Filament wound fiberglass (E-801) in a foam sandwich and AISI 347 stainless steel are chosen for weight comparisons tabulated in Tables II - VII

      1. Table II shows the weight of the two-man, one-lock chamber depicted on Figure 2.
      2. Table III illustrates the weight savings (nearly 100 lbs.) to be gained should the collapsibility requirement for this concept be deleted.
      3. Tables IV and V are similar to II and III except AISI 347 stainless steel shells are substituted for the fiberglass sandwich construction.
      4. Table VI shows the weight of the two-man, two-lock chamber depicted on Figure 8.
      5. Table VII illustrates the increase in weight of the two-man, two-lock chamber if fabricated from AISI 347 stainless steel.

   b. Comments regarding other candidate materials:

      1. S-glass (S-994) has highest strength-to-weight ratio of all materials listed, but its superiority over E-glass cannot be utilized effectively because the minimum recommended wall thickness from a manufacturing viewpoint is greater than the strength requirement.
      2. Wrought carbon and low alloy steel are discarded because of a lack of corrosion resistance and relatively poor strength-to-weight ratios.
      3. The high strength of 17-7 ph and similar steels cannot be utilized effectively without heat treatment after welding. Due to the anticipated difficulty in heat treating such a large diameter vessel, the non-heat treated stainless steel AISI 347 was selected for weight comparison with the fiberglass structure.
      4. The high strength aluminum 7178-T6 is not applicable due to poor weldability. Aluminum 6061-T4 can be welded satisfact-

orily although the full material strength cannot be utilized without heat treatment after welding. A vessel fabricated from 6061-T4 aluminum offers no advantage over 347 stainless when designed for equal stiffness.

5. Titanium and magnesium were discounted for obvious reasons; the former due to its very poor workability and high cost, the latter because of its fire hazard in oxygen rich atmospheres in addition to engineering reasons.

3. Thickness of pressure shells and other stressed structure was calculated using ASME code (Section VIII) design procedure and material strengths where applicable. Where ASME code did not apply, namely for fiberglass, an equivalent design strength factor was utilized, i.e., 25% of ultimate strength.

4. The selection of fiberglass is made on the basis of its inherent corrosion resistance as well as its light weight. A "sandwich" of fiberglass and foam adds sufficient stiffness while still resulting in a considerable weight savings over other candidate materials. In addition, the sandwich construction is a good thermal insulator and sound attenuator, two benefits not found in the metallics.

   a. A fiberglass sandwich construction with 75% of the stiffness of an equivalent ASME stainless steel design *(as determined critical bending moment calculations) weighs less than 75% of the latter.

   b. Fiberglass and foam sandwich has been proven feasible from both manufacturing and usage viewpoints as demonstrated by UTC report Project 1313-"Design and Fabrication of Prototype Fiberglass Shipping/Conditioning Container for Solid Rocket Motor Segments" (February 1964). This study was followed by a contract calling for production of over 30 such containers.

      Basic manufacturing techniques were established in the referenced study, including attachments of hardware, such as lifting rings, covers, seals, etc.

      The durability of fiberglass in actual field usage has been demonstrated. To quote the referenced report, "The Navy's glass-reinforced plastic container for the Polaris missile is probably the best example of long-term usage of such a product. With over four years of actual trouble-free field service, it can be concluded that glass-reinforced plastic was the best material selection for the job".

*See Appendix II

5. Based on the above considerations, a fiberglass-foam sandwich construction was chosen for both prime chamber concepts:

   a. One-lock Chamber, Figure 2.

      1. Attendant chamber wall-1" overall thickness with 1/16" filament wound inner shell and 3/32" outer shell (filament wound or fiberglass lay up).
      2. Patient module wall: not applicable.

   b. Two-lock Chamber, Figure 8.

      1. Patient chamber walls - 3/4" overall thickness with 1/16" inside and outside fiberglass shells housing 3 lb/ft^3 polyurethane foam.
      2. Attendant chamber walls - 1/2" overall thickness with 3/32" inside and outside fiberglass shells. Inner shell is filament wound but outer shell may be lay-up construction.

6. Possible Modifications to the above described construction are:

   a. Substitution of honeycomb structure or balsa wood for the foam fill. This may prove cheaper at no cost in stiffness or weight.

   b. Major junctures in the filament wound inner shell such as the patient-attendant module intersection (see Figure 2a) have not been developed in previous shells. Therefore, the concepts shown on the referenced drawing are subject to change in a development program, but represent a sound starting point for design of a prototype or feasibility chamber.

TABLE I

Material	Ultimate Strength Lb/in^2	Density $\frac{Lb.}{In^3}$	$\frac{\text{Strength}}{\text{Weight}}$ Ratio	Modulus of Elasticity Lb/in^2	Approximate Cost of Basic Material (Heat Treat and Fabrication Cost Not Included)
Fiberglass (Filament Wound) S-994	*185,000	.072	2,570,000	$6x10^6$	$4.00
E-801	*127,000	.072	1,760,000	$6x10^6$	.50
Wrought Carbon Steel (AISI 1010)	40,000	.283	142,000	$30x10^6$	.20
Wrought Low-Alloy Steel (AISI 4130)	160,000	.283	565,000	$29x10^6$	.35
Stainless Steel AISI 347	75,000	.290	258,000	$29x10^6$	1.00
17-7 ph	240,000	.280	866,000	$30x10^6$	1.00
Aluminum 7178-T6	94,000	.101	930,000	$10x10^6$	1.15
6061-T4	30,000	.098	306,000	$10x16^6$	.90
Titanium B-120-VCA	125,000	.175	1,260,000	$15x10^6$	7.50
Magnesium A231B	38,000	.065	588,000	$7x10^6$	1.30

Material strengths from HSD Materials Manual
*From "A Fiberglass (Spiralloy) Hyperbaric Facility for Clinical Use" by R. Adams Cowley and G. Sheldon Gordon

TABLE II

Weight Breakdown Table for a Two-Man, One-Lock Chamber (Figure 2.) with Convoluted Bellows

Fiberglass Construction with Collapsible Convoluted Patient Module

Attendant Module:	
Shell and Door	123
Transition Section	21
Wheels and Brackets (3 sets)	17
Pass Thru, View Ports and Misc	24
Patient Module:	
Convoluted Bladder	35
Support Rings	32
Support Rails and Hinges (4 sets)	108
End Cap	17
Front Wheel Assembly	15
Stretcher	8
	400 lbs.

TABLE III

Weight Breakdown Table for a Two-Man, One-Lock Chamber with All Fiberglass Construction, with Non-Collapsible Patient Module

Attendant Module:	
Shell and Door	123
Transition Section	21
Wheels and Brackets	17
Pass Thru, View Ports and Misc.	24
Patient Module:	
Shell	84
End Cap	17
Front Wheel Assembly	15
Stretcher	8
	309 lbs.

TABLE IV

Weight Breakdown Table of Two-Man, One-Lock Chamber with "ASME" Stainless Steel Attendant Module and Collapsible Convoluted Patient Module

Attendant Module:	
Shell and Door	186
Transition Section	21
Wheels and Brackets	21
Pass Thru, View Ports, and Misc	27
Patient Module:	
Convoluted Bladder	35
Support Rings	67
Support Rails and Hinges	108
End Cap	27
Front Wheel Assembly	17
Stretcher	8
	517 lbs.

TABLE V

Weight Breakdown Table of Two-Man, One-Lock Chamber of all "ASME" Stainless Steel Construction with Non-Collapsible Patient Module

Attendant Module:	
Shell and Door	186
Transition Section	21
Wheels and Brackets	21
Pass Thru, View Ports and Misc	27
Patient Module:	
Shell	122
End Cap	27
Front Wheel Assembly	15
Stretcher	8
	427 lbs.

TABLE VI

Weight Breakdown Table for a Collapsible, Separable, Two-Man, Two-Lock Chamber of Fiberglass Construction
(Ref Figure 8)

Attendant Module:	
Shell, hatches, and frame, interlock, flange	276
Casters, support structure, support rest	25
V-band coupling	15
Pass-thru view ports (two), misc hardware	44
	360 lbs.
Patient Module:	
Shell, hatch, storage and interlock flanges	207
Bladder and stretcher	12
Casters and support structures	37
Pass-thru, view ports (3), fan, phone, misc hardware	44
	300 lbs.

Combined weight, both modules = 660 lbs.

TABLE VII

Weight Breakdown Table
For a Collapsible, Separable, Two-Man, Two-Lock Chamber of "ASME" Stainless Steel Construction

Attendant Module:		
Shell, hatches, and interlock flange	359	
Casters, support structure, support rest	25	
V-band coupling	15	
Pass-thru, view ports (two), misc hardware	44	
	443	lbs.
Patient Module:		
Shell, hatch, storage, and interlock flanges	416	
Bladder and stretcher	12	
Casters and support structures	37	
Pass-thru, view ports (3), fan, phone, misc	44	
	509	lbs.

Combined weight, both modules = 952 lbs.

C. FUNCTIONAL DESCRIPTION OF TWO-MAN ONE-LOCK CHAMBER WITH CONVOLUTED BELLOWS (Figure 2).

1. General Description:

The one-lock chamber is a minimal weight and volume vehicle for two men. The width dimension is selected to allow passage through standard width doors. The patient and attendant modules are not detachable but may be transported as a unit directly to the mother chamber, where pressurized transfer of patient and attendant may occur thru an adapter (not shown on Figure 2). The closed loop ECS is mounted on a separate cart and is linked to the chamber during transportation by an umbilical which provides the gas inlet and outlet, electrical power and supplementary oxygen or air. The umbilical may be disconnected by separating self-sealing quick disconnects. Auxiliary connectors are provided for simultaneous attachment of an open loop system during periods when such a system is available. At these times, the closed loop system will be shut-down and conserved. The open loop system would not normally accompany the chamber during transportation, but would constitute a more economical ECS during periods when the chamber remained at one location, such as dock side operation, or hospital standby when the "Mother" chamber is not available.

When not in operation, the chamber may be collapsed for storage to an envelope of less than 3 feet wide by 5 1/2 feet high and 5 feet long. (Chamber extended length is 9 feet).

Collapse of the patient module is executed as follows: (Refer to Figure 2).

a) Remove the quick operating lock pins which fasten the support channels to the end cap and detach the longitudinal wheel support struts.

b) Roll the end cap assembly toward the attendant module until all support rings are beyond the channel hinges.

c) Detach the forward channel sections and lash the fully collapsed patient chamber to the rear channels. (The detached channels and wheel struts will store easily in the attendant module).

2. Component Description Details:

a. Attendant Module

1) The attendant module is a 32 inch I.D., 34 inch O.D. cylinder with domed ends. The attendant is positioned at the head of the patient in this concept and is somewhat more restricted than in the larger attendant module shown on Figure 8. However, all modules will accommodate the 99 percentile man (reference: NASA Bioastronautics Data Book SP-3006). The one inch thick wall is a sandwich of two relatively thin fiberglass shells encasing a thick layer of polyurethane foam. The inner filament wound shell

comprises the pressure vessel. The outer shell and foam serve to add stiffness and durability as well as provide insulation from the environment. The basis for the selection of the foam-fiberglass sandwich is outlined in Section B.

2) The major penetrations in the attendant module are the door, the transition section to the patient module, the medicant pass-thru and the viewports. Figure 2 sheet 2 shows conceptual details for executing these penetrations. In each case, emphasis is placed on properly reinforcing the area around the penetration so as to distribute the "plug" load evenly into the fiberglass structure around the opening. The doorframe and transition section are particularly critical; therefore, stainless steel is selected for these components to obtain maximum stiffness. Thin edge rings are provided to protect the fiberglass edge around the openings.

The method of "locking in" the frames is a new technique and has not been executed in current fiberglass structures as depicted, although the differences may be academic. The current method for reinforcing around penetrations in fiberglass wound shapes is one of inserting thin steel discs between successive layers of fiberglass and drilling or cutting the opening after winding is complete. An annular ring remains after cutting the opening, thru which bolt holes are drilled for attaching the mating flange. Bolts are not required for the concept shown on Figure 2a, eliminating the need for an extra seal at each penetration.

3) The attendant chamber door is an ellipse of 2 feet by 3 feet, allowing internal mounting and pressure sealing without the use of heavy structural latches. Four lightweight cam latches hold the door in place until pressurization occurs. The door is of the same construction as the basic chamber. The silicone rubber seal is bonded in a groove in the stainless steel frame which provides protection from accidental damage.

4) The pass-thru lock is virtually all fiberglass construction. Its internal volume (5 1/2 inch diameter by 11 inch length) will accommodate a quart container. The outboard door incorporates redundant seals insuring leak-tightness. Fast-actuating clamps hold the hatch. The pressure sealing inner hatch is hinged and a simple clip arrangement holds the door in place until pressurization occurs.

5) The 3/4 inch thick, 7 inch diameter tempered pyrex viewport is retained in its aluminum housing by a stainless steel ring which also protects the adjacent fiberglass edge around the port. The port allows observation of the attendant, while somewhat smaller viewports in the transition section allow close observation of the patient's head and chest area. Also, a port may be incorporated in the end cap to observe the patient's lower extremities; such observation being desirable for circulatory problems.

6) The attendant module is supported by three casters mounted on stainless steel support brackets. The support brackets are bolted to steel plates imbedded in the foam between the fiberglass shells, a technique developed by United Technology Center (UTC), in which steel plates are placed in the foam prior to fabrication of the outer shell (see UTC report referenced in Section B.4.b.).

Semi-pneumatic tires provide a reasonably shock free ride for the occupants, while not requiring pressure filling as for fully pneumatic tires.

7) A combination pressure relief and chamber depressurization valve is manually operated from the outside. The pressure relief setting is adjustable and the valve acts automatically to relieve excess pressure, but may be overridden by an outside attendant in response to readings observed on the wall mounted pressure gauge adjacent to the valve. A temperature gauge is also provided in close proximity. Two pressure relief valves are recommended for safety and reliability.

8) The attendant chamber also incorporates appropriate lifting rings and carrying handles (which also serve as the tie-downs). Four aircraft type self-sealing quick-disconnects facilitate integration of the ECS. A hermetically sealed pin and socket electrical connector feeds power to the internal air circulation fans and implosion proof lights, as well as the bio-instrumentation. A collapsible stool is provided for the attendant.

Bio-instrumentation, electrical equipment, and medical equipment are discussed in more detail elsewhere.

b. Patient Module:

The patient module consists of a collapsible pressure retaining rubber bladder, circumferential support rings, longitudinal, hinged, support channels, and an end cap and wheel assembly.

1) Convoluted Chamber Wall:

The wall is a rubber and fabric composite similar in construction to materials currently being utilized in the Apollo Space Suit Program. However, the size of the patient chamber presents manufacturing problems not encountered in the space suit; namely, fabrication of a 27 inch O.D. convoluted shape. However, consultations with the AGC Inc. of Meriden, Conn., and the Firestone Industrial Products Division of Firestone Tire & Rubber Company resulted in the conclusion that the concept is feasible, although a development program is required to establish the most economical method of fabrication.

One candidate material for the chamber is black neoprene coated nylon twill per MIL-C-9277A (Par. 3.3.2). Should the dipping process prove feasible, a latex dip over three layers of nylon oxford cloth (MIL-C-7219 T III) will provide a composite with an ultimate strength of approximately 900 lbs. per inch of width (a single layer has an ultimate strength of 275 lb/in. in the weave and 325

in the fill). The convolution cross-section is semi-toroidal with a one inch radius. This shape induces a stress of *45 lb/in of width in the longitudinal direction and 90 lb/in. in the circumferential when supported with rings and channels as shown on Figure 2. A tapered convolution was considered, but discarded after a brief investigation indicated that envelope and collapsibility were not significantly improved, while support problems were increased.

2) Convolution Support Rings:

The support rings, as shown on Figure 2 serve dual purposes; circumferential support of the bladder and protection of the convolutions; especially in the collapsed posture, in which the overhanging outer periphery of the rings abut each other and completely encase the collapsed convolutions. However, the weight penalty of the overhang is approximately 40 lbs. (total for 28 rings) even when the rings are fabricated from fiberglass. Since a less sophisticated, but lighter means of protection is available for storage, such as a tarpaulin, the weight of the overhanging ring periphery is not included in the weight tables. The basic support ring thickness is one-eighth inch, providing adequate strength (see appendix). Four "T" shaped tabs are located equally spaced around each ring O.D. for guiding the rings in the longitudinal channels.

3) Longitudinal Support Channels:

Four removable channels accept the 20 ton "plug" load on the end cap caused by the 6 atmospheres absolute maximum operating pressure. The channels also serve as tracks to guide the support rings during extension and compression of the chamber and stabilize the patient chamber during transporation by bridging between the end cap and transition section. The rear channel sections are firmly secured to the transition with two 3/4 inch diameter steel bolts each. Each forward channel is detachable from the end cap clevis through extraction of the quick-actuating lock pin. The hinges adequately transmit the channel load from the forward to the rear sections while allowing for easy separation of the forward channels for storage after collapse of the chamber.

The core of each channel is a 3" X 1.41" American Standard Steel Channel. Fiberglass lay-up is performed over the channel to give it the appropriate shape to serve as a track for the "T" shaped tabs on the support rings. The hinges are welded to the steel core prior to lay-up.

4) The end cap is of the same construction as the attendant module wall (fiberglass-foam sandwich). Handles and wheel support brackets are attached to the end cap using conventional techniques described in the previously referenced UTC report. A viewport may also be incorporated.

*See Appendix II

5) The front wheel assembly consists of seamless aluminum tubular struts, semi-pneumatic tires mounted on a steel axle, and detachable longitudinal wheel supports.

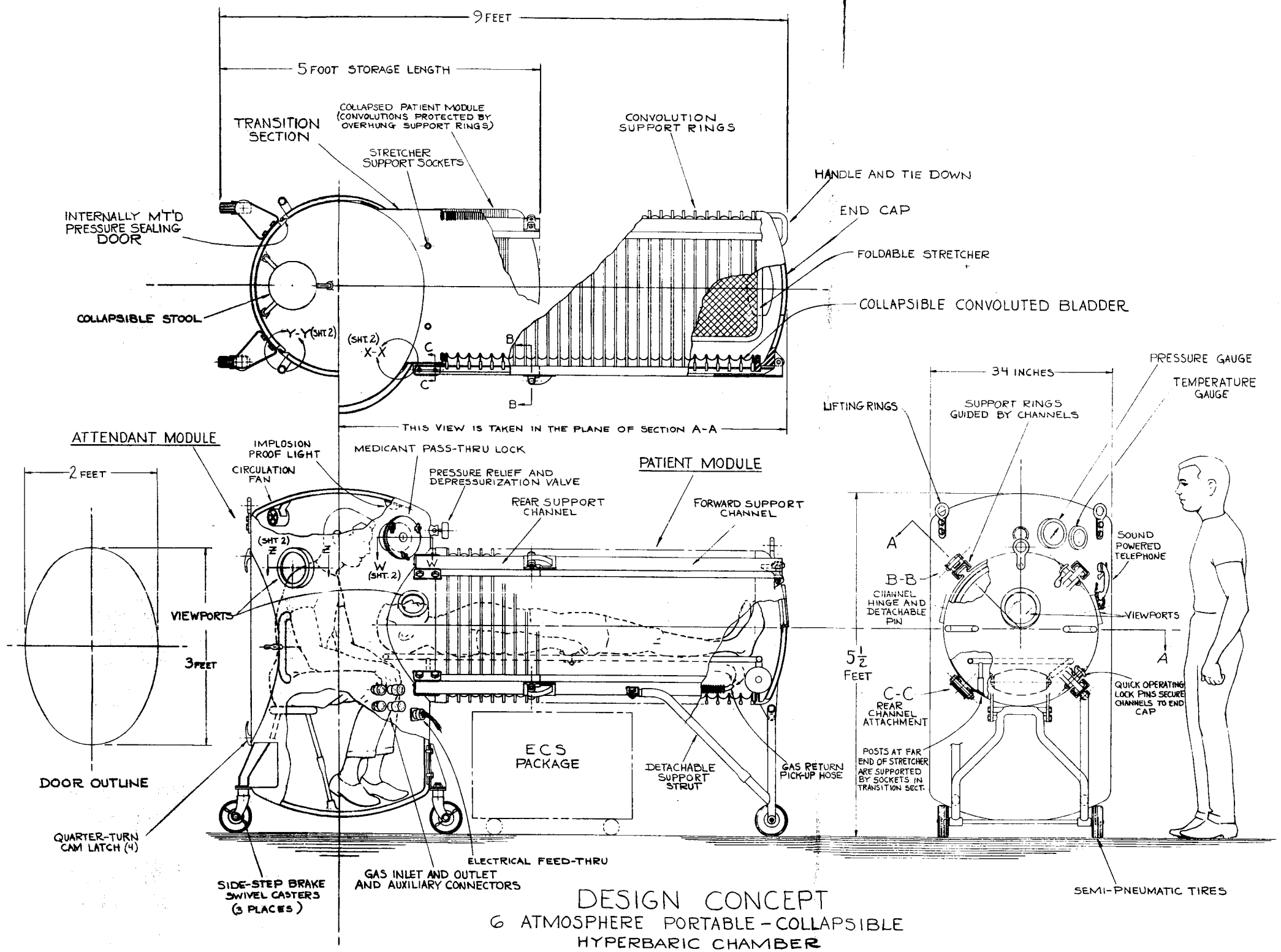
3. Alternate Convoluted Design:

The Firestone Industrial Products Division of Firestone Tire & Rubber Company provided an alternate design using "off the shelf" techniques employed in making "Air-Ride" pneumatic suspension systems. While the required diameter of 30 inches is not presently available, the Division proposes tooling to make production of these chambers feasible.

Appendix VI illustrates the Firestone design which consists of four 3 - convolution bellows plus three intermediate spacer sections for a total unit length of 6 feet 3.5 inches. An advantage of this design is the ability to disassemble and easily replace a damaged section.

4. Scale Model

In order to more clearly and effectively demonstrate the features and concepts of this design, a 1/6 scale model has been constructed and included as part of the end products of the study. Figures 3 through 7 illustrate the configurations of the chamber system from storage through operation modes.



DESIGN CONCEPT
6 ATMOSPHERE PORTABLE - COLLAPSIBLE HYPERBARIC CHAMBER
(1/6 SIZE)

APPROVAL	SIGNATURES	DATE
DESIGNER	Mellalieu	2/66
DESIGNER'S SUPV.	DAMM	2/66
DESIGN ENGINEER		
CHIEF DESIGN ENGR		
PROJECT ENGR		
DESIGN STAFF		

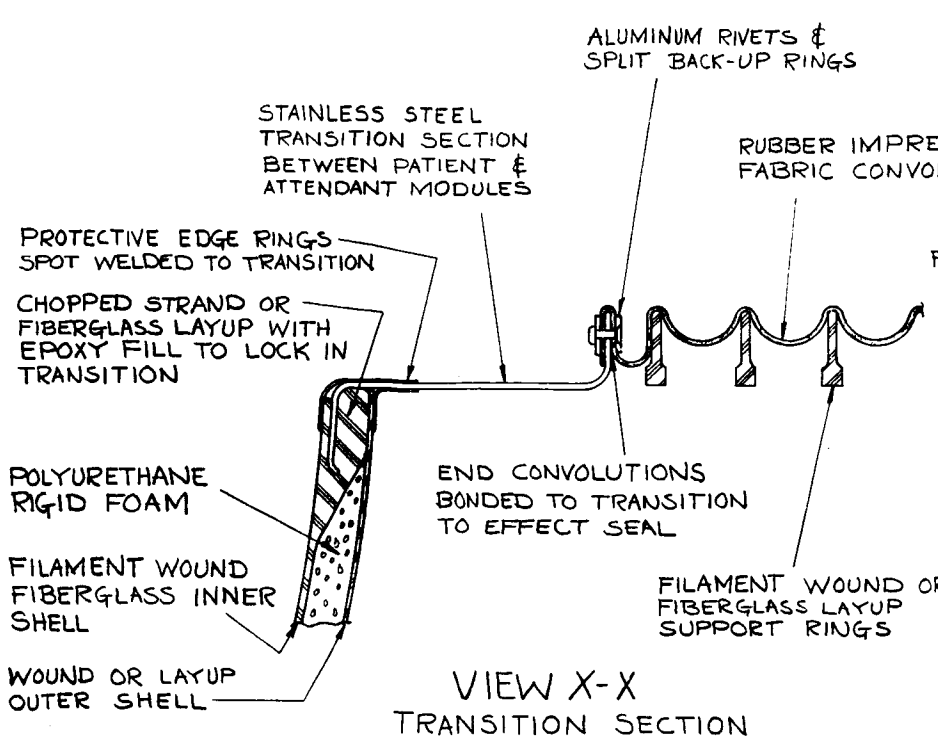
Hamilton Standard — 3/10/66

HYPERBARIC CHAMBER TWO MAN - ONE LOCK, CONVOLUTED PATIENT MODULE

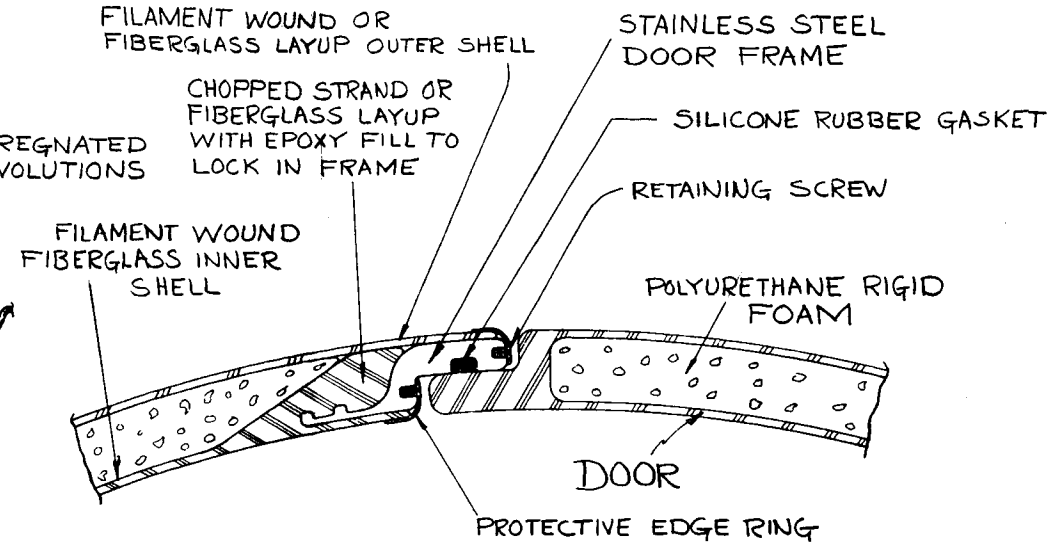
SIZE: A | CODE IDENT NO.: 73030 | SVSK-62524

SCALE: 1/6 SIZE | WEIGHT: | SHEET 1 OF 2

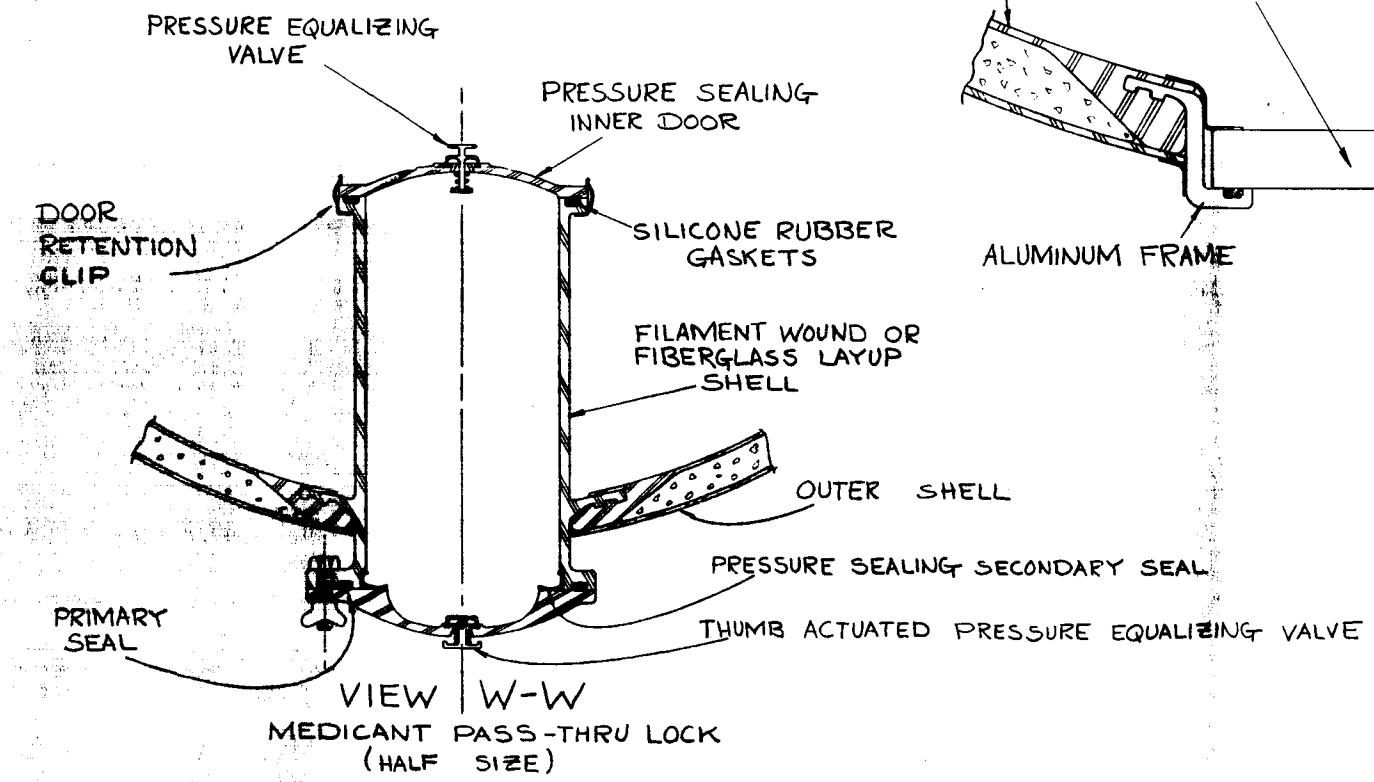
FIGURE 2



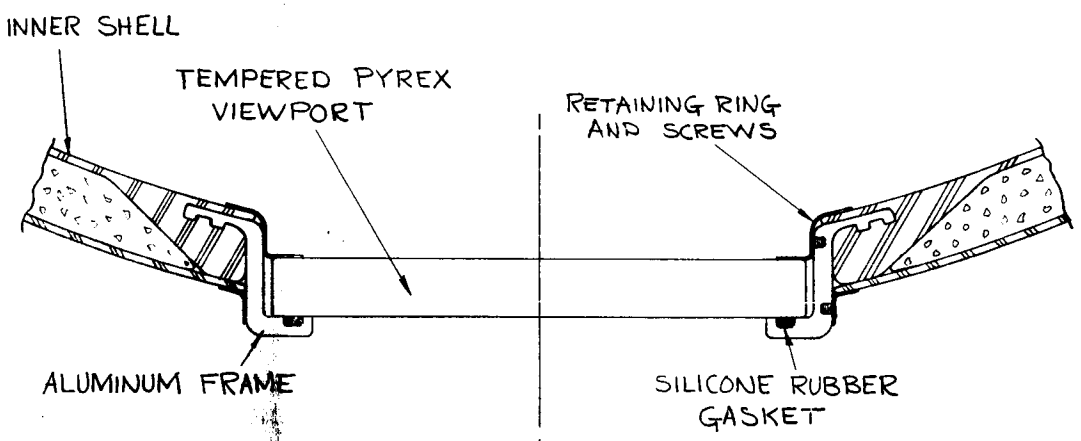
VIEW X-X
TRANSITION SECTION
(HALF SIZE)



VIEW Y-Y
DOOR AND FRAME DETAIL
(FULL SIZE)



VIEW W-W
MEDICANT PASS-THRU LOCK
(HALF SIZE)



VIEW Z-Z
VIEWPORT
(FULL SIZE)

3/18/66

UNLESS OTHERWISE SPECIFIED:								
DIMENSIONS ± ____ ANGLES ± ____. EXCEPT FOR DRILL END FORMS, FILLET RADII ____ TO ____ SURFACES HAVING A COMMON AXIS CONCENTRIC WITHIN ____ TIR. ____ BREAK EDGES .002 - .025				△MARK PART IDENTIFICATION: MIL-STD-130 PER HS333. DRAWING INTERPRETATION PER ____, CLEANING, PRESERVATION AND HANDLING PER HS1550-C ____P____. SURFACE CHARACTERISTICS PER ____			NEXT ASSY	USED ON
INSPECT-TEST DESIGNATED AREA(S) PER		MATERIAL		DRAWN	Mallalieu	3/66	APPLICATION	
				CHECKED				
				DESIGN	Dunn	3/66		
DES	SPECIFICATION(S)			DFTG		COST	Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION WINDSOR LOCKS, CONNECTICUT, U.S.A.	
△A		HARDNESS		MAT'L		FCTY		
△B		HEAT TREAT		PROJ		Q & R	HYPERBARIC CHAMBER DETAILS	
		SPEC		CONTRACT NUMBER				
		SURFACE COATING		EXP MFG	PRELIM PROD.	PROD.	SIZE: D	CODE IDENT NO.: 73030
		MFG SPEC					DRAWING NO.: SVSK-62524	
ALL AREAS		MAKE FROM					SCALE:	WEIGHT: LB
		PROD. CODE					SHEET 2 OF 2	

FIGURE 2a

D. FUNCTIONAL DESCRIPTION OF TWO-MAN TWO-LOCK CHAMBER WITH TELESCOPING TUBE DESIGN (FIGURE 8).

1. General Description:

This chamber allows transportation of the patient (in the patient module) directly into the "mother" chamber after disconnecting the attendant module. The mother facility may then be pressurized and patient transfer at the desired pressure setting can be executed without the need for an adapter as in the one-lock concept. Indeed, the patient chamber, with detached wheel assemblies, forms a 34 inch diameter by 7 foot long envelope which is compatible with virtually all multi-man size hyperbaric facilities now in operation.

The open or closed loop ECS may be connected to either the attendant or patient module in the same fashion as described in the previous section for the one-lock chamber. Detachment of the modules may occur while preserving the high pressure atmosphere in either or both modules (hatches for this purpose are stored in the attendant module and installed prior to separation by the attendant). The ECS is then transferred to one of the modules by operating the appropriate quick disconnect(s) and attaching a second ECS to the other module.

In cases where patient chamber disconnection occurs at or near the hospital or military hyperbaric facility, a second ECS is not usually required. A safe CO_2 level will be maintained in the patient chamber after disconnecting the ECS for at least 20 minutes, allowing time to transfer the patient to the larger facility.

Disconnection of the attendant and patient modules is executed by releasing the "V" band coupling after installation of the inner hatches by the attendant. The "T" bolt and trunnion assembly on the "V" band coupling is interlocked with a depressurization valve which bleeds the small gas volume between the chambers to ambient pressure. The interlock is required to assure safe separation of the modules precluding premature release of the coupling. After separation of the chambers, the coupling is remounted to the attendant chamber flange until the chambers are again mated, for the next usage or for storage.

Storage of the chambers, with full collapse of the patient module for minimum envelope, may be accomplished by two men as follows:

1) Disconnect and collapse the patient chamber:

   a) remove longitudinal wheel support struts and foldable stretcher.

   b) fold-out the bladder using hand loops provided while telescoping sections are being collapsed.

c) insert and latch chamber hatch.

2) Attach collapsed patient chamber to attendant module:

a) remove front wheel assembly and store with stretcher in attendant module.

b) turn patient chamber 180° and insert into attendant chamber.

c) attach "V" band clamp.

d) rear wheel assembly is detachable but may remain in place for storage mode. Storage envelope is 4 feet long by 5-1/2 feet wide by 5-1/2 feet high (extended length is 10 feet with chambers attached; 7 feet, patient module only).

2. Component Description Details:

a. Attendant Chamber:

1) Attendant chamber is sized to give 99th percentile man (per Bio-Astronautics Data Book) required working space when in sitting position.

2) Twin automatic depressurization valves are interlocked to the two V-band coupling T-bolts. Each of these interlocks must be disconnected before its respective T-bolt and nut can be disassembled. Both patient-interlock hatch and attendant-interlock hatch are installed by attendant before these interlocks are disconnected. Thus the depressurization valves bleed-off interlocking chamber pressure, thereby preventing sudden separation of the two chambers.

3) Circular pressure sealing attendant-interlock hatch, installed by attendant in preparation for chamber separation, is normally stored just inside main entrance hatch (on attendant's left) during interlocked mode of operation. All hatches may be placed outside during patient's entry into chamber to allow maximum working space inside attendant chamber.

4) Main entrance hatch is elliptical to permit hatch removal from chamber and utilize pressure-sealing action on "O" ring. Each hatch is provided with four quarter-turn cam latches which also serve as handles during hatch installation and removal. The cam latches on the attendant interlock hatch are operable only from the attendant chamber.

5) Three lifting rings, on spherical surfaces near top of chamber, permit power lift of patient chamber. One is located on each side of main entrance hatch. The third is centered on interlock side of chamber. Stainless steel eyes are imbedded in fiberglass bosses which are bonded to outer fiberglass chamber shell.

6) Three carrying handles permit transportability over irregular terrain and stairs. One handle wraps around corner from spherical section to cylindrical section. The other two handles are on opposite spherical surfaces near intersection of spherical with cylindrical section. The two handles are located in position to best support extra weight of patient. These carrying handles also serve as tie downs for shipping and shipboard operation.

7) Two swivel casters, with foot-operated brakes, facilitate short-distance manual transportability over relatively smooth horizontal surfaces. Mounting of casters to fiberglass is similar to mounting found on two-man, one-lock attendant module. (Paragraph C.2.a.6.) A fiberglass "foot" is located opposite two casters and is used in detached mode to support attendant chamber in lieu of another caster.

8) Medical pass-thru lock, located high on wall opposite attendant is constructed similar to that in the convoluted chamber (Paragraph C.2.a.4).

9) Implosion proof light, near top of chamber, is constructed similar to light described for patient chamber.

10) Sound-powered telephone provides communication between attendant and personnel outside chamber.

11) Folding seat bracket is mounted on fiberglass boss. Seat is folded upwards when not in use.

12) Pressure relief and depressurization valve permits chamber bleed-off by personnel outside chamber in addition to functioning as safety device.

13) Electrical harness provides power for light and circulation fan. The electrical feed-thru is accomplished by hermetically-sealed pin-and-socket electrical connector.

14) Chamber pressure and temperature gauges have readout dials outside chamber in area near depressurization valve.

15) Two view ports allow medical observation of patient and/or attendant. One view port is high on main entrance hatch. Second view port is on cylindrical surface faced by attendant.

16) Four self-sealing quick-disconnect gas fittings are described in Paragraph B.2.a.8.

17) The air circulation fan is located in a manner such that its outflow will not impinge directly on the patient or attendant.

18) Chamber shell construction is similar to that described in Paragraph C.2.a.1) except I.D. is 60 inches, thickness of wall is 1-1/2 inches with 3/32 layers of fiberglass inside and outside. Spherical sections shown on Figure 8 vary slightly from ovaloid recommended in UTC report "Evaluation of 22 Inch Diameter Geodesic Ovaloid Filament-Wound Bottle".* This variation inflicts a slight weight penalty for attainment of superior working space inside the module, although design of a prototype chamber would require further evaluation of this trade-off.

b. Patient Chamber:

1) Patient chamber is sized for 99th percentile man (per Bioastronautics Data Book) on foldable stretcher in prone position.

2) Three telescoping sections collapse for compact storage. A larger number of sections allows more compact patient module storage; but because of attendant configuration chosen and the required hardware and accessories, the overall storage length of both units would not be decreased. Conversely, a smaller number of sections would substantially increase storage length and consequent volume. Shell construction is similar to Paragraph C.2.a.1, except wall thickness is 3/4 inch and fiberglass is 1/16 inside and outside.

3) V-band coupling locks attendant chamber to patient chamber to form one two-man chamber. V-band coupling advantages over bolted flange for this application are as follows:

a) V-band coupling requires less than 20% of time necessary to separate chambers utilizing the number of bolts required to assure no leakage at "O" ring.

b) V-band coupling minimizes seal pressure variation (around circumference) typical in bolted flanges.

* See Appendix III.

c) V-band coupling permits easier mating flange alignment.

d) Bolted flange requires wrench clearance around each bolt which may force some hardware into undesirable locations.

V-band coupling disadvantages are as follows:

a) Bolted flange provides automatic pressure relief as bolts are loosened.

b) Bolted flange permits attachment of lifting rings and caster-support structure to flanges providing better local stress distribution.

4) Additional flange (storage flange) and 180° rotation of patient module prior to storage inside attendant module became necessary to achieve minimum storage/shipping volume and retain face-type seal (superior to radial seal for this application).

5) Elliptical patient-interlock hatch permits removal of hatch from chamber and incorporates desirable pressure-sealing action on "O" ring. Four lightweight quarter-turn cam latches position hatch until pressure activates seal and serve as handles during hatch-installation and removal. Hatchway flange is bonded in place after telescoping sections are assembled.

6) Lifting rings (one located near each end of patient module) permit power lift of patient chamber.

7) Carrying handles permit transportability for short distances over irregular terrain and stairs. These handles also serve as tie downs. One handle is on spherical end of small end-section and also provides sockets for mounting caster support structure. Two handles (one on each side) are located between storage flange and interlock flange on O.D. of large end-section. The two handles at hatch end are located close enough to patient module centerline to keep overall width down to 34 inches but far enough from wall O.D. to permit finger space. These handles are provided at a convenient carrying height.

8) Four casters facilitate medium-distance manual transportability over relatively smooth horizontal surfaces (one-man transporting is possible with detached patient module). Two fixed casters at flanged-end and two swivel casters at small end provide dynamic stability and ease of handling

from small end. This arrangement also provides increased stability and requires less turning space during interlocked mode of operation. The two swivel casters are supplied with foot-operated brakes.

9) A bladder is bonded to the two end sections to contain the pressure inside the chamber. The bladder material is nylon fabric coated on both sides with neoprene rubber. The bladder is held in place at the mid section by snap fasteners which maintain bladder position when chamber is not pressurized. Rubber hand loops are bonded to inside of bladder to facilitate fold-out of bladder during collapse of telescoping sections for storage or shipping.

10) All hardware penetrating the pressure vessel wall, except the view port at small end of chamber (vicinity of patient's feet), is located on the cylindrical wall between the storage and interlock flanges. This location is chosen for all penetrations to allow insertion of the collapsed patient module into the attendant module for the storage mode, while maintaining the smallest possible flange diameter.

a) Medicant pass-thru lock permits passage of required medication to patient. It is located near top of large end-section to right of centerline (patient's right as he lies on his back). Wall and doors are fiberglass. Valves are stainless steel.

(1) Pressure sealing inner hatch is mounted on hinge. Thumb-actuated bleed valve pressurizes lock interior to chamber pressure before inner hatch can be opened. Valve hinge and "O" ring are assembled on hatch; then hatch assembly is installed after telescoping sections are assembled.

(2) Outer hatch is equipped with double seal ("O" ring plus face-type). Thumb screws effect "O" ring seal. Pressure effects face-type seal. Manually operated pull-valve bleeds lock pressure to ambient before thumb screws are removed.

b) Implosion-proof light overhead (inside chamber) is operable from inside for convenience of patient or from outside chamber to permit observation of patient. Bulb is replaceable from outside chamber to allow replacement during pressurized chamber operation. Lens is installed from inside after telescoping sections are assembled.

c) Sound-powered telephone provides communication between patient and personnel outside chamber.

d) Pressure relief and depressurization valve permits chamber pressure bleed-off by personnel outside chamber in addition to functioning as a safety device.

e) Electrical harness provides bio-medical monitoring and power for fan and light.

f) Chamber pressure and chamber temperature gages have readout dials outside chamber.

g) Four view ports permit medical observation of patient. One view port on each side of chamber allows view of patient's head and chest area. One view port is located at the foot of the chamber to permit observation of peripheral vascular damage. An additional port is located in the hatch. Tempered pyrex sight glass is installed from inside chamber with gasket on each side and threaded ring holds glass in place.

h) Four self-sealing quick-disconnect gas fittings provide environmental control system supply and return.

(1) Gas inlet supplies revitalized gas to vicinity of patient's head.

(2) Flexible hose ducts exhaust gas from vicinity of patient's feet to gas outlet.

(3) Two auxiliary quick-disconnect fittings may be used with open loop ECS.

11) An air circulating fan is located inside chamber between storage and interlock flanges (beneath head-end of stretcher). Fan is installed after telescoping sections are assembled.

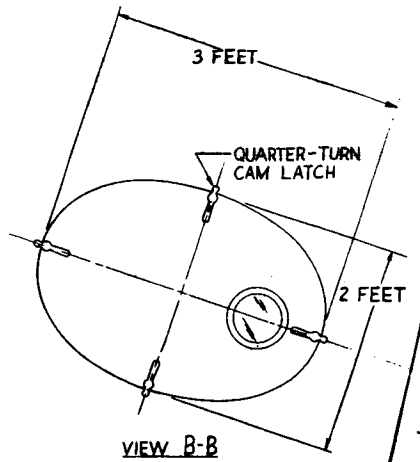
12) Two stretcher-support posts, mounted on inside wall of large end-section near storage flange, support stretcher. They keep head-end of stretcher off the bladder, keep stretcher horizontal, and eliminate side-to-side stretcher movement with respect to chamber.

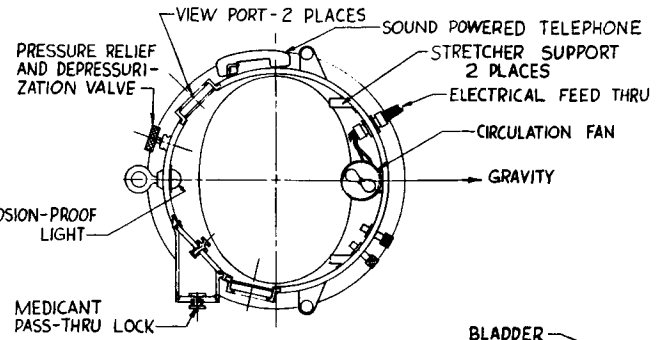
13) Stretcher facilitates patient entry into chamber. Hinges near center permits folded stretcher to be stored in attendant module when collapsed patient module is in storage mode. Soft rubber roller at foot of stretcher affords a

high degree of roll stability concurrent with bladder protection and ease of maneuvering patient. Four sockets bonded to stretcher frame allow stretcher to assume two positions. One pair of sockets locate patient completely within patient chamber for detached mode of operation. Second pair of sockets position patient's head and shoulders approximately one foot into attendant module when chambers are connected.

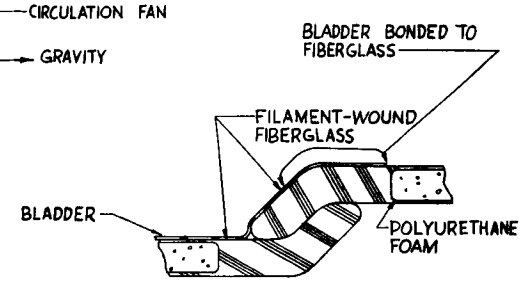
3. Scale Model:

A 1/6 scale model of this chamber concept was also constructed for more effective presentation of the design. Figures 9 through 13 illustrate the progressive changes in chamber modes from storage to operational use as a two-man chamber and finally separated into two one-man chambers.

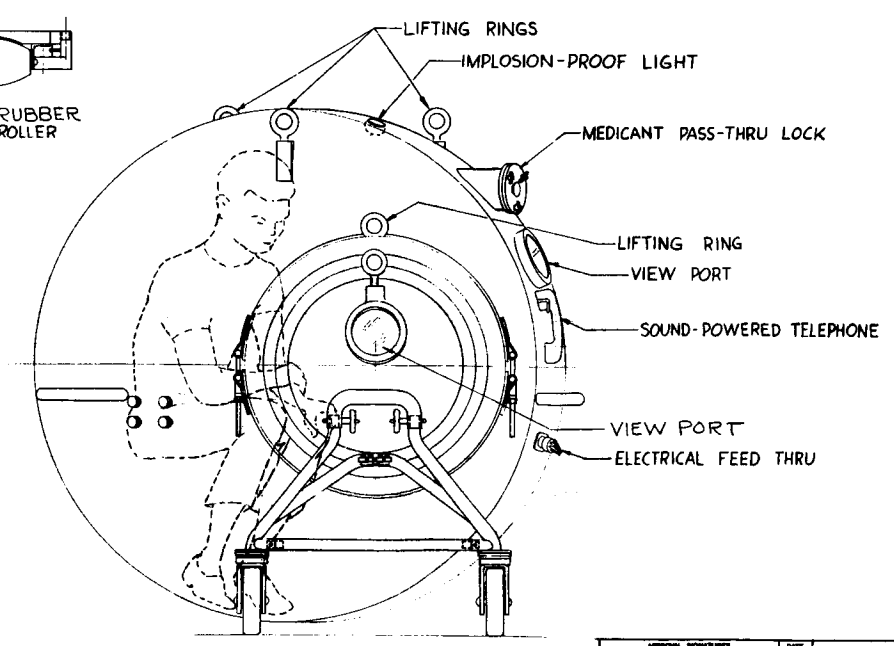




SECTION A-A



DETAIL Z-Z FULL SIZE



APPROVAL SIGNATURES		DATE	Hamilton Standard
DESIGNER	[illegible]	12/14/66	
DESIGNER'S SUPV.	[illegible]	12/66	CHAMBER, HYPERBARIC, TWO-LOCK, TELESCOPING PATIENT MODULE
DESIGN ENGINEER			
CHIEF DESIGN ENGR			
PROJECT ENGR			SIZE: B — CODE IDENT NO: 73030 — SVSK 62525
DESIGN STAFF			SCALE: 1/8 — WEIGHT: — SHEET: 1 of 1

DESIGN CONCEPT - 6 ATMOSPHERE PORTABLE - COLLAPSIBLE HYPERBARIC CHAMBER
(1/6 SIZE)

FIGURE 8

E. COMMON EQUIPMENT:

With each chamber concept there is the associated environmental control system or systems (ECS) which provides the proper internal chamber environment. In addition, bio-instrumentation is provided for monitoring of the patient and, perhaps, attendant as desired.

1. Environmental Control Systems:

a. General Background:

One object of the study was to define feasible systems for temperature, pressure, humidity, and contaminant control of the hyperbaric chamber. Feasibility was to be considered in terms of size, weight, power requirement, and cost.

Two types of systems were studied - closed loop and open loop. A limited survey of commercially available components was performed to incorporate low cost off-the-shelf hardware into the system wherever possible.

The specifications to which the system was designed, as extracted from the Performance Specification, were:

Chamber Pressure	:	14.7 - 88.2 psia
Chamber Temperature	:	75 ± 5° F
Chamber Humidity	:	65 ± 5%
Pressurization Rate	:	14.7 psia/min (minimum)
Ambient Temperature	:	-20 to 140° F
Metabolic Rate	:	700 BTU/HR/occupant
Occupants	:	1 patient and 0 or 1 attendant

b. Parameters and General Approach:

The specific parameters which affected system design were metabolic rate, ambient heat leak, circulating fan power, maximum pressure level, chamber temperature, chamber humidity, and pressurization rate. In the open loop system the pressure level is maintained by opening a valve in the chamber and allowing through flow of the air. In the closed loop system the chamber is pressurized from compressed air tanks and the air is circulated through an ECS system. The resulting size of this ECS system was smaller for the closed loop since the open loop system required an ECS system which would raise the air pressure from 14.7 psia to a maximum of 88.1 psia. For both systems the following extreme ambient conditions were considered:

(a)	T	=	140°F	and RH	= 1.2%
(b)	T	=	90°F	and RH	= 100%
(c)	T	=	20°F	and RH	= 100%

Since these conditions are extreme, a smaller, lower power ECS unit could be sized if these are relaxed. In the case of the closed loop system, that which would most likely be utilized during transportation and hence most critical in regard to weight, size and power requirements, additional analysis was performed utilizing a less extreme but still very adequate environmental temperature upper limit.

c. Closed Loop Hyperbaric ECS:

1) General:

The study closed loop system is shown schematically in Figure 14. This system was studied to determine relative size, weight, power requirement, and cost. Dehumidification and cooling is performed by a direct expansion freon system combined with a relatively small, lightweight, plate-fin heat exchanger. In order to accommodate the wide ambient temperature range, subcooling and reheating are necessary and an electrical heater follows the evaporator.

The chamber and system are pressurized by expanding compressed air from storage bottles through a pressure regulating valve into the recirculation system upstream of the evaporator. The fan flow control valve is fully closed so that the expanding air flows through the evaporator and heater, and is cooled or heated to obtain a comfortable chamber temperature.

When pressurization is completed, the fan control valve is opened, the fan is energized, and recirculation occurs. A temperature sensing control at the chamber outlet maintains a constant chamber temperature by controlling the evaporator expansion valve. A chamber thermostat can be used to control the heater. Carbon dioxide, odors, and foreign particles are removed in the canister, passing first through activated charcoal, then soda lime, and finally a cloth filter. The canister cartridge is of a low pressure drop, radial flow design employed in the present LEM vehicle for NASA and Grumman.

A purging valve located on the chamber is employed for reducing chamber pressure as necessary.

2) Parametric Study:

The specification condition of $140^{\circ}F$ ambient at the maximum design pressure of 88.2 psia was considered for the sizing

of the fan, freon condensing unit, and evaporator. The air mass flow rate is a maximum at the maximum pressure, and the chamber heat load is a maximum at the maximum ambient temperature. Figure 15 shows the variation of chamber inlet temperature, and chamber outlet humidity with flow rate for the specification outlet temperature range. This curve is based on a heat balance equating the net heat production in the chamber to the heat gained by the air in passing through the chamber; and by balancing the latent metabolic production rate with the difference in the water vapor flow at the outlet and inlet of the chamber. The inlet air is assumed to be supplied at the evaporator outlet temperature without any reheating. The curve shows that reheating is not necessary in the flow range of 380 - 700 lb/hr.

In Figure 16 the average chamber temperature is then plotted versus air flow rate with the constant humidity lines of 60% and 70%. The area bounded by the constant outlet temperature lines and the constant humidity lines then represents the area in which the specifications can be met without reheating the evaporator outlet air. The variation of the of the system power requirements with flow rate is presented in Figure 17. Both fan power and evaporator heat load increase with flow; fan power increases very slightly with outlet temperature, while the heat load decreases slightly. The minimum power requirement occurs at minimum flow.

For reasons of comfort, the minimum average chamber temperature was set at 70°. Figure 16 shows that the minimum required flow rate for a 70° average temperature occurs at the highest outlet temperature. Therefore, the system was designed for an 80°F outlet temperature. Figure 19 is a flow chart showing the system operation at this design point.

The amount of reheat that would be necessary to obtain a 70° average temperature at a lower flow rate is shown in Figure 18. A dashed line shows the corresponding decrease in the fan power requirement.

The heater was sized for -20°F ambient temperature and maximum system flow rate, with one occupant, metabolic rate of 400 btu/hr. The system operation at this condition is shown in Figure 20. The reheat required at this condition represents the maximum amount that could be needed, and was used for reasons of safety. The minimum required amount would be many times less.

3) Significance of Ambient Temperature:

The maximum design operating ambient temperature has a very significant effect on the size and power requirements of the environmental control system. For example, redesign of the closed loop system for a maximum ambient temperature of 90°F, rather than 140°F, results in a component weight saving of 10 pounds, a power saving of 485 watts, and a theoretical cost saving of $32, all of which occur mainly in the refrigerant condensing unit.

The savings realized from the reduction in ambient temperature are due to a decrease in chamber heat leak from 584 Btu/hr @ 140°F to 125 Btu/hr @ 90°F and to the reduction in condensing temperature. These result in a lower design flow rate, a lower fan power requirement, and a lower cooling capacity refrigerant condensing unit with a much lower compressor power requirement.

4) Assumptions:

The system was designed for a reasonable amount of comfort within the temperature and humidity specifications. A minimum average temperature of 70°F was assumed, and with the inclusion of two circulation fans in the chamber it was assumed that sufficient convection would occur to prevent thermal sweating. Therefore, the only source of latent heat and moisture would be respiration and skin diffusion from the chamber occupants. The skin diffusion rate was assumed to be constant at 0.0655 lb/hr per person, and the respiratory perspiration was assumed to be proportional to metabolic rate, and equal to 0.000063 lb/hr per Btu/hr metabolic.

The carbon dioxide production rate was assumed to be proportional to metabolic rate, and equal to 0.195×10^{-5} lb/hr per Btu/hr metabolic. In calculating the temperature rise and water vapor production rate in the soda lime canister, it was assumed that the carbon dioxide reduction rate was equal to the chamber production rate. In heat transfer calculations the chamber was assumed to be constructed with the following materials:

Fiberglass	3/16" thickness	$k = 1.9$ Btu/hrft^2 °F/in
Plastic foam	1" thickness	$k = .14$ Btu/hrft^2 °F/in

Solar radiation was neglected in heat transfer calculations at 140°F ambient since it was assumed that in such an environment sufficient shading would be provided; and at -20°F since it would decrease system requirements.

A wind velocity of 10 mph was used in calculating the convection coefficient on the outside chamber wall. The variance of this value with wind velocity was insufficient to affect the calculated overall heat transfer coefficient.

Heat transfer from ambient to the system components and ducting was neglected. If the system is not sufficiently insulated to prevent considerable heat transfer, the heating or cooling load will increase, and will necessitate a larger condensing unit, evaporator, and heater. An air duct size of 2" I.D. was used in determining system pressure drops. Sample calculations are included in the appendix.

The following list of component requirements indicates what performance is expected from each major component. Typical units which satisfy these requirements have been selected from various commercial and aerospace companies and are tabulated in Figure 21.

5) Closed Loop System Component Requirements:

(1) Recirculation System - All components must operate satisfactorily at pressures of 14.7 - 100 psia.

(a) Carbon Dioxide Removal Canister:

The canister must be capable of removing a minimum of 0.273 lb/hr of carbon dioxide for a period of not less than 8 hours. The pressure drop across the canister must not exceed 2.1 in. H_2O at an air flow rate of 507.5 lb/hr at 88.2 psia. The canister will be in use at inlet temperatures of 70-80°F, and relative humidity of 60-70%.

(b) Recirculation Fan:

The fan must provide an air flow rate of 507.5 lb/hr at 88.2 psia, 83°F inlet with a minimum fan pressure rise of 3.92 in. H_2O. The input power must be variable from 0 to 135 watts maximum.

(c) Evaporator:

The evaporator must have the capacity to remove a minimum of 3600 Btu/hr from air entering at 507.5 lb/hr, 88.2 psia, 88.3°F, 55.5% R.H., and exiting at 60°F, 100% R.H. The cooling fluid will be 40°F freon. The pressure drop at the above conditions must not exceed 0.97 in. H_2O.

(d) Heater:

The heater must have the capacity to raise the temperature of air flowing at 507.5 lb/hr, 88.2 psia, 52.1°F, 100% R.H. a minimum of 21.6°F. The input power must be adjustable from 0 to a maximum power input of 800 watts.

(e) Air Cooled Refrigerant Condensing Unit:

The unit must have a minimum capacity of 3600 Btu/hr at a suction temperature of 40°F and an ambient temperature of 140°F. It must be equipped with an expansion valve controlled by an adjustable temperature sensor (65 - 85°F), a low pressure control to prevent freezing in the evaporator, a dryer, and a liquid level and moisture indicator. The power consumption must not exceed 965 watts, including the power consumed by the condenser fan.

(f) Air Flow Control Valve:

The valve must act both as a check valve and a flow control valve. The pressure drop at an air flow rate of 507.5 lb/hr at 88.2 psia, 86°F must not exceed 0.18 in. H_2O.

(2) Pressurization System:

(a) Compressed Air Supply:

The initial pressure must be a minimum of 2000 psia, and the total volume must be a minimum of 350 ft^3 STP.

(b) Pressure Regulating Valve:

The valve must pass a minimum air flow rate of 60 SCFM at a supply pressure of 200 psia.

(c) Purging Valve:

The chamber purging valve must pass an air flow rate adjustable from 0 to 60 SCFM minimum from a chamber pressure of 29.4 psia to ambient.

(3) Chamber Circulation:

(a) Circulation Fans (2)

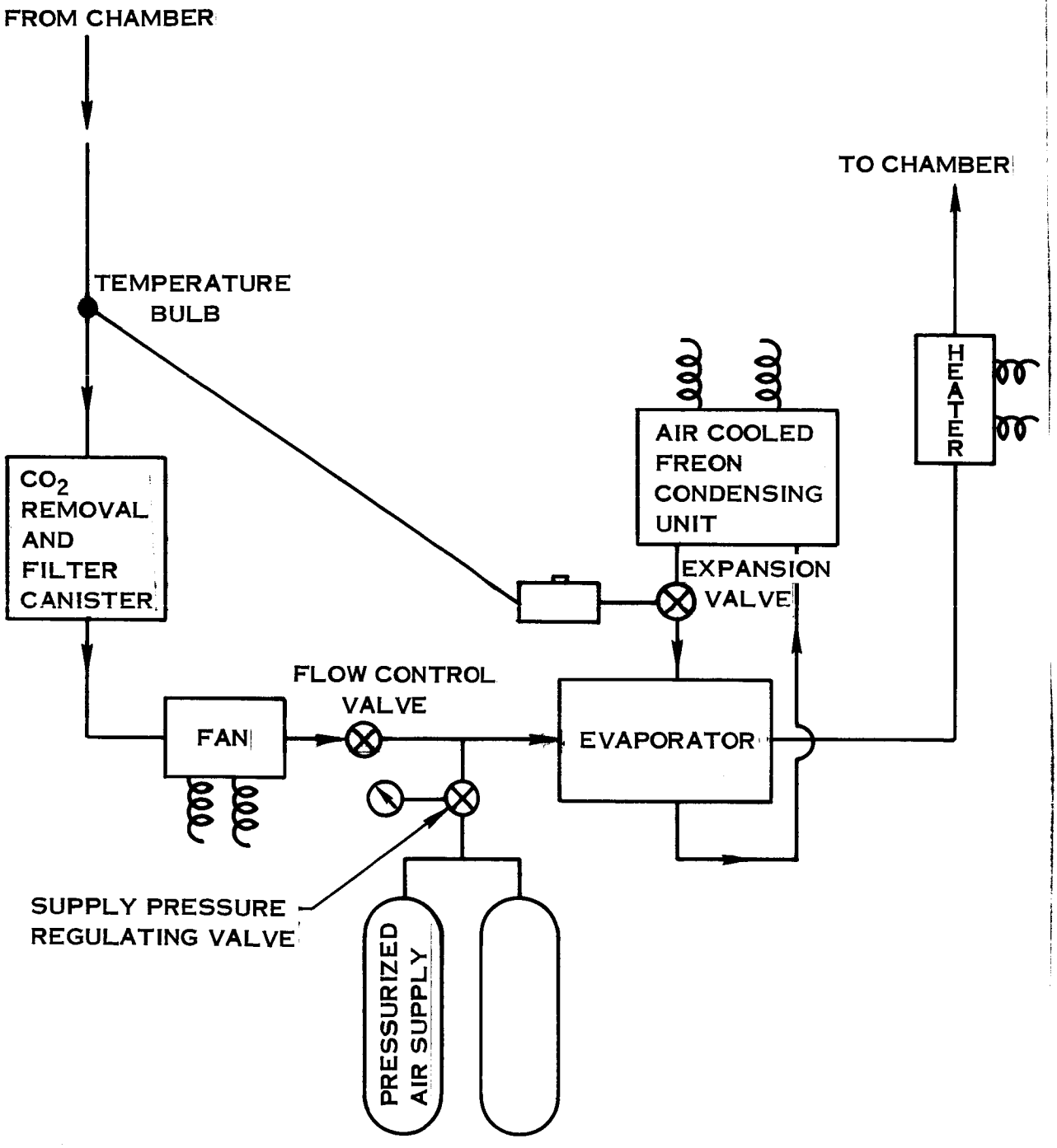


FIGURE 14. SCHEMATIC OF HYPERBARIC CHAMBER AIR RECIRCULATION SYSTEM

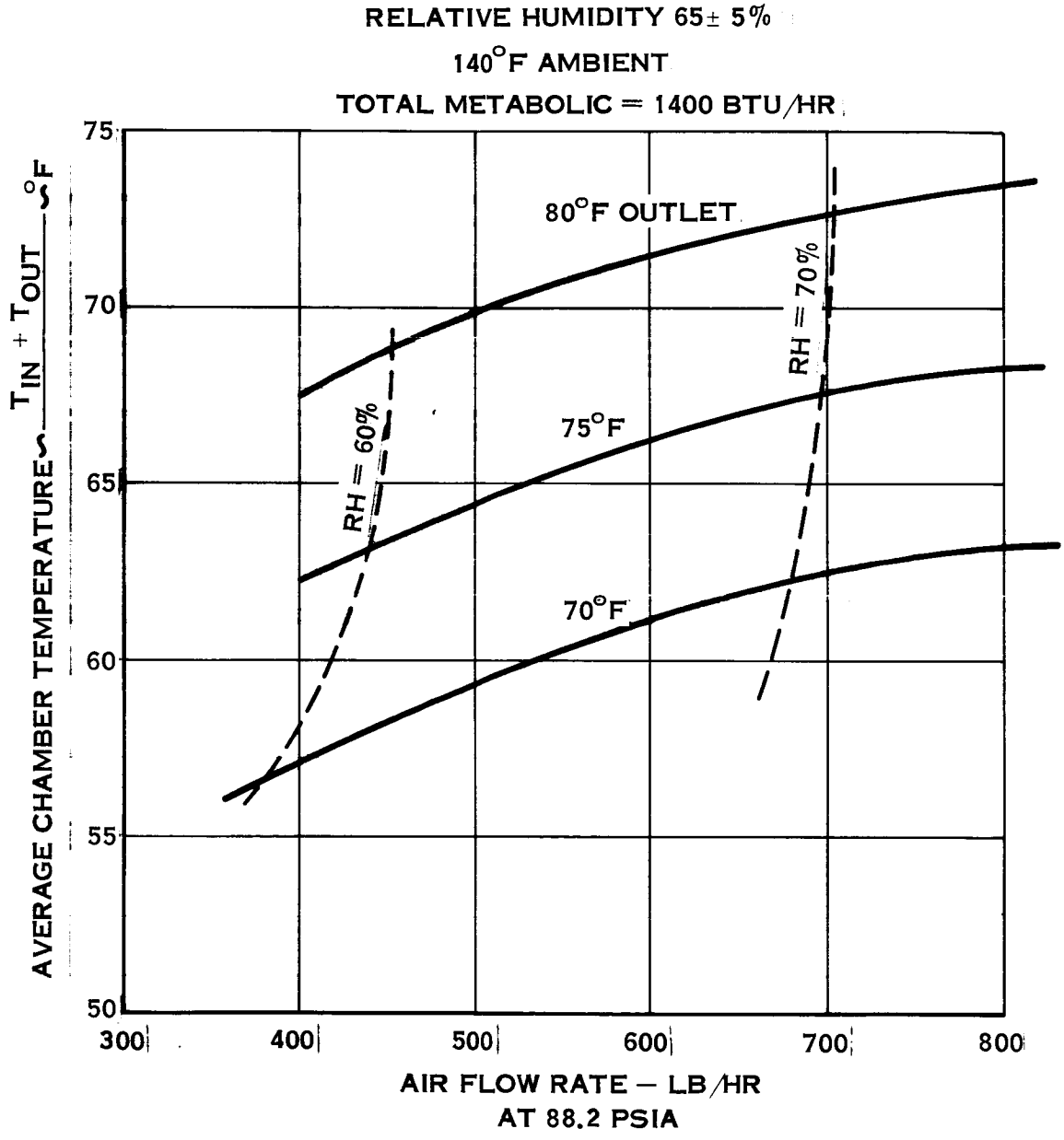


FIGURE 16. AVERAGE CHAMBER TEMPERATURE VS. FLOW RATE FOR CHAMBER OUTLET TEMPERATURE 75 ±5°F

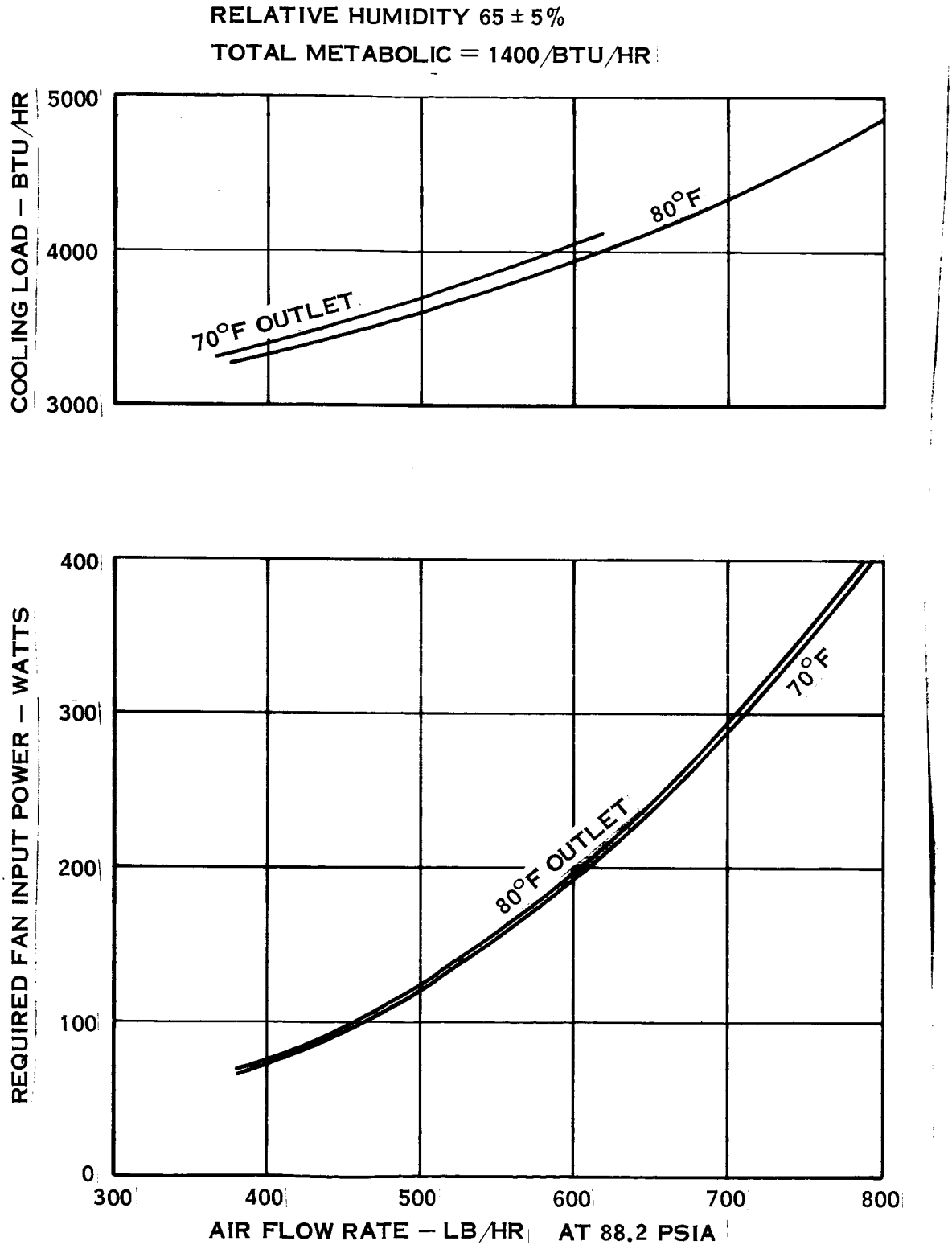


FIGURE 17. REQUIRED FAN INPUT POWER AND EVAPORATOR LOAD VS. FLOW RATE FOR CHAMBER OUTLET TEMPERATURE 75 ± 5°F

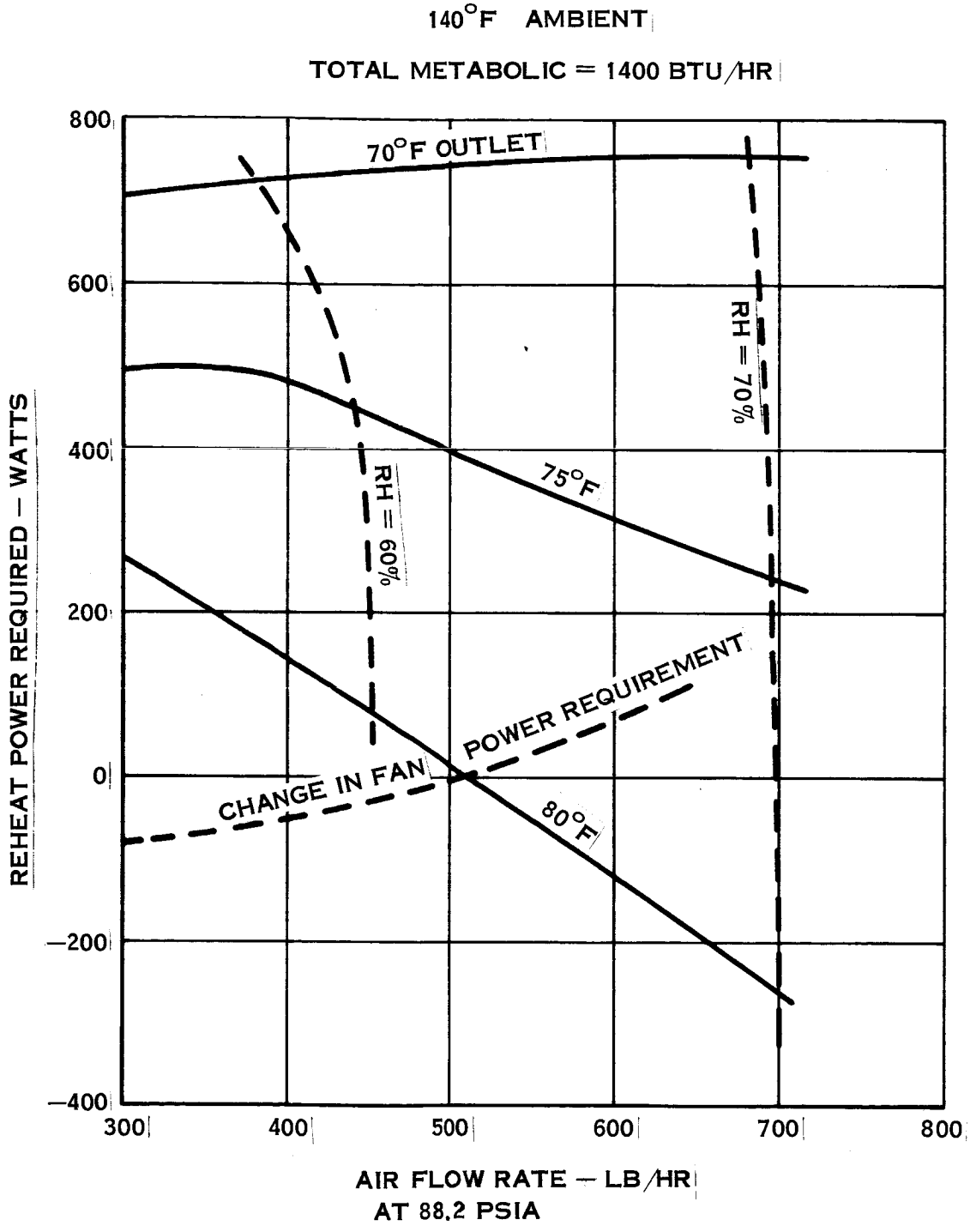


FIGURE 18. REHEAT NECESSARY TO RAISE AVERAGE CHAMBER TEMPERATURE TO 70°F VS. AIR FLOW RATE AT 88.2 PSIA

SUMMARY CHART OF COMPONENTS FOR CLOSED LOOP SYSTEM FOR HYPERBARIC CHAMBER

Item	Estimated Size	Lbs. Estimated Weight	Dollars Estimated Cost	Possible Source
Carbon Dioxide Removal Canister	8" OD x 10"	16 (including 7 Sodalime)	--	HSD LEM - Modified for 88 psia soda lime - W. R. Grace Company
System Fan	4" O.D. x 4"	4	--	Joy Mfg. Co., Mod. No. AVF 33-26D1228 with modified motor
Evaporator	4" x 4" x 6"	4	--	HSD Design
Heater	3" O.D. x 6"	4	--	Chromalox, Inc.
Condensing Unit and Accessories	10" x 14" x 20"	70	135	Tecumseh Products Co.
Flow Control Valve	3" x 4"	1	--	Supply Company
Purging Valve	3" x 4"	1	8	Supply Company, Henry Products #6231 $\frac{1}{4}$" ODS
		100 lbs		
Compressed Air Bottles (2)	9" x 55"	130 x 2	10	Ohio Chem. & Surg. Equip. Co. 2000 psig size H.
Pressure Regulating Valve	8" x 8" x 8"	5	50	Matheson Company, two stage regulator #9.
Circulation Fans	5" x 5" x 3"	2.5 x 2	--	Torrington Co. STA-410 Series
		270 lbs		

Figure 21

The fan must provide a variable air flow rate of 0 - 120 cfm with a minimum static pressure rise of 0.25 in. H_2O at 88.2 psia ambient. The input power must not exceed 100 watts.

d. Open Loop Hyperbaric ECS:

1) General:

The maximum ECS power occurs when the maximum compressor pressure ratio, dependent upon chamber pressure level, is maintained. As such, a chamber pressure of 88.1 psia was used as the design case. For this case, the flow rate was selected on the basis of a 60 cubic foot chamber and a minimum fill rate of 1 atmosphere per minute, or 10 cfm based on chamber ambient conditions. The dependence of fill rate and ambient cfm on flow is shown in Figure 22. The fill rate of one atmosphere per minute is felt to be a reasonable fill rate and still 25% above the U.S. Navy Diving Manual value of 8 cfm required when 2 men are using oxygen or using air, but not at rest. If the minimum requirement of 8 cfm (3.56 lb/min) was used the fill rate would be 0.78 atmospheres per minute, and a resultant saving of approximately 25% could be achieved in power and a saving of approximately 20% could be achieved in ECS component size and weight. As such, the fill rate should be lowered in an effort to incorporate this reduction in size and weight. Figure 23 shows the heat leak associated with various through flows on the basis of a forced convection film coefficient on the inside of the hyperbaric chamber. Although two fans are proposed for the occupants' comfort, it was assumed that these fans would not increase the through flow and boundary velocities.

However, they would increase the convective cooling of the occupants as per the values shown in Figure 24. These values are based on past experience in testing and analysis of manned space suits under the Apollo EMU contract from NASA. Since the volume flow through the ECS compressor is approximately constant as ambient conditions change, the 140°F ambient temperature determines the maximum flow required to obtain a given pressurization rate. The chamber relative humidity was allowed to vary with the comfort zone given by the "Heating Ventilating Air Conditioning Guide 1960." As such, a chamber temperature of 75°F had an allowable variation in relative humidity of 30% to 70% while still remaining well within the comfort zone.

The basic system utilizes a compressor followed by the refrigeration system as shown in Figure 25. This figure

shows the high air temperatures and refrigeration loads resulting from the compression of air to achieve the required 88.1 psia chamber pressure. The extremes of temperatures and powers (also sizes and weights) dictated the use of one or more water to air heat exchangers employing sea water at 90°F. Again, the 90°F sea water temperature is considered an extreme and the resultant component sizes are considered the maximum possible required.

Figure 26 includes the use of just one heat exchanger which yields a two stage compressor with intercooling. The intercooling will be an air-water aircraft type plate and fin heat exchanger. The pump to feed the sea water to the heat exchanger will maintain a flow of 240 lb/hr and will require 0.1 hp. The power required by the two stage compressor is slightly lower than a single stage compressor and greatly reduces high temperature, pressure and tip speed stresses. The refrigeration unit will also be slightly smaller because of the intercooling.

Since the heat exchanger is small in size, the use of two as shown in Figure 27 is highly recommended. This results in lower air temperatures and compressor temperatures which will yield an increased component life along with lower stresses, powers and sizes. Sea water was also used to cool the refrigeration condenser. As such, a smaller refrigeration system requiring less power was used. The power variation with ambient temperature variations was also minimized and greater control of evaporator outlet air temperature is possible. Air from environment is drawn into the line and undergoes compression from 14.7 psia to 37 psia in compressor #1. It is then cooled in the #1 heat exchanger and flows into compressor #2. Compressor #2 brings the pressure up to approximately 93.2 psia. The #2 heat exchanger cools this compressed air down before it enters the evaporator. The air is cooled in the evaporator by a cold freon vapor flow from a refrigerating unit. As the air is cooled water vapor is condensed out and an evaporator provision will be made to wick this condensation to a collection pan from which it can be drawn off.

Control of the outlet air temperature from the chamber will be maintained by a sensing element located at the chamber outlet to the refrigerating expansion valve. Temperature of the chamber outlet saturated air will be held at 75°F. This will serve to hold the chamber temperature and relative humidity at their desired levels. A comparison of the ECS requirements using none, one, or two heat exchangers is given in Figure 28.

The design condition of 90°F and 100% relative humidity are conservative and a more representative relative humidity of 70% would yield a decrease in power as well as size of the refrigeration system. Since approximately half the refrigeration load is latent, the 70% relative humidity would result in a saving in power and weight of the refrigeration unit of approximately 15% as estimated below:

	Present Design	New Design	Saving
	90°F, 100% R.H.	90°F, 70% R.H.	
weight	247 lbs.	210 lbs.	37 lbs.
power	3.9 hp	3.3 hp	0.6 hp

The use of sea water as a coolant can be very corrosive. As such, the heat exchangers should be flushed with fresh water after the chamber has been used. Another alternative would be to emerse the enclosed air fins in sea water and in effect make a sea-water boiler rather than a heat exchanger. As such, corrosion could be eliminated and the water pumping power minimized to just that required for the refrigeration condenser.

System #3 is considered feasible even with the extremes of requirements selected. For this system, the various components have been sized and a possible vendor indicated. A summary of this system selection is shown in Figure 29. The major components of this system have been selected from catalog information. In many cases aircraft components are used because of the savings in power and weight achieved by using these components. All electrical components are selected for a 115 V A.C. 60 cycle source. In the case of lack of this power source, battery power with an inverter could be utilized.

The air compressors are Stratos Units, Model ACR5, normally used as dry air pumps for de-icing. The 18 pound weight includes a gear box to mount to the motor. The ideal calculated compressor input power is 7.75 hp, whereas this unit requires 8.2 hp input.

The motors used to drive the compressors are selected from catalog data published by Benson Manufacturing Company. The motor has 80% efficiency with an output of 10.5 hp and an input of 13.0 hp. The ideal motor-compressor input would be approximately 10 hp. Thus, this selected combination is slightly overpowered. However, a more thorough investigation of vendor products could yield a 10 hp input unit.

The heat exchangers and evaporator for the refrigeration unit are based upon HSD's past experience in heat exchanger technology. The size was selected on the basis of low pressure drop and relatively high performance (85% effectiveness) within a moderate size. The fins and geometry of these units is based upon heat exchanger technology acquired from aircraft and spacecraft (LEM) applications.

The Carrier refrigeration unit (model 6D41) uses Freon 12 refrigerant and has a water-cooled condenser. The use of a water-cooled condenser allows a smaller size than an air-cooled condenser and also results in less variation in power and evaporator air outlet temperature with variation in ambient temperature. As such, a more stable unit results for a very small increase in water pumping power. The refrigeration unit is the systems heaviest component and any reduction in ambient humidity or temperature will decrease the required size and weight. The water for cooling is pumped by a 1/3 hp available from Eastern Industries. Since most commercial pumps are relatively high capacity units the division of water flow into parallel paths utilizes the high quantity of flow available and yields much smaller, lighter, ECS equipment.

Before entering the chamber, a Filterite filter with a particle selection of 10 microns is employed. This filter is available for operation up to 100 psig and can readily be modified for use up to 250 psig if necessary.

Inside the chamber two modified Torrington fans circulate the flow. These fans can move up to 100 cfm each, but new motors will be necessary to move the high pressure air. The compatibility of these fans with high pressure oxygen present in the air has not been thoroughly investigated, but if necessary oxygen compatible motors can be incorporated. These would be the type presently being employed in the Apollo Portable Life Support System and the LEM ECS. However, if motors of this type are necessary, they would have to be developed for this application.

Operation at lower humidities than 1.2% on a 140° day would result in lower chamber humidities. For the metabolic loads selected, zero water vapor in the air would result in a chamber relative humidity of 18% which is still comfortable. As such, low relative humidities present no problem. Since the compressor work increases air temperature considerably, a refrigerant bypass will allow warmer air to enter the chamber on cold days and still maintain the required 75° internal temperature.

The operation of the chamber at less than 6 atmospheres is easily accomplished by opening a pressure control valve.

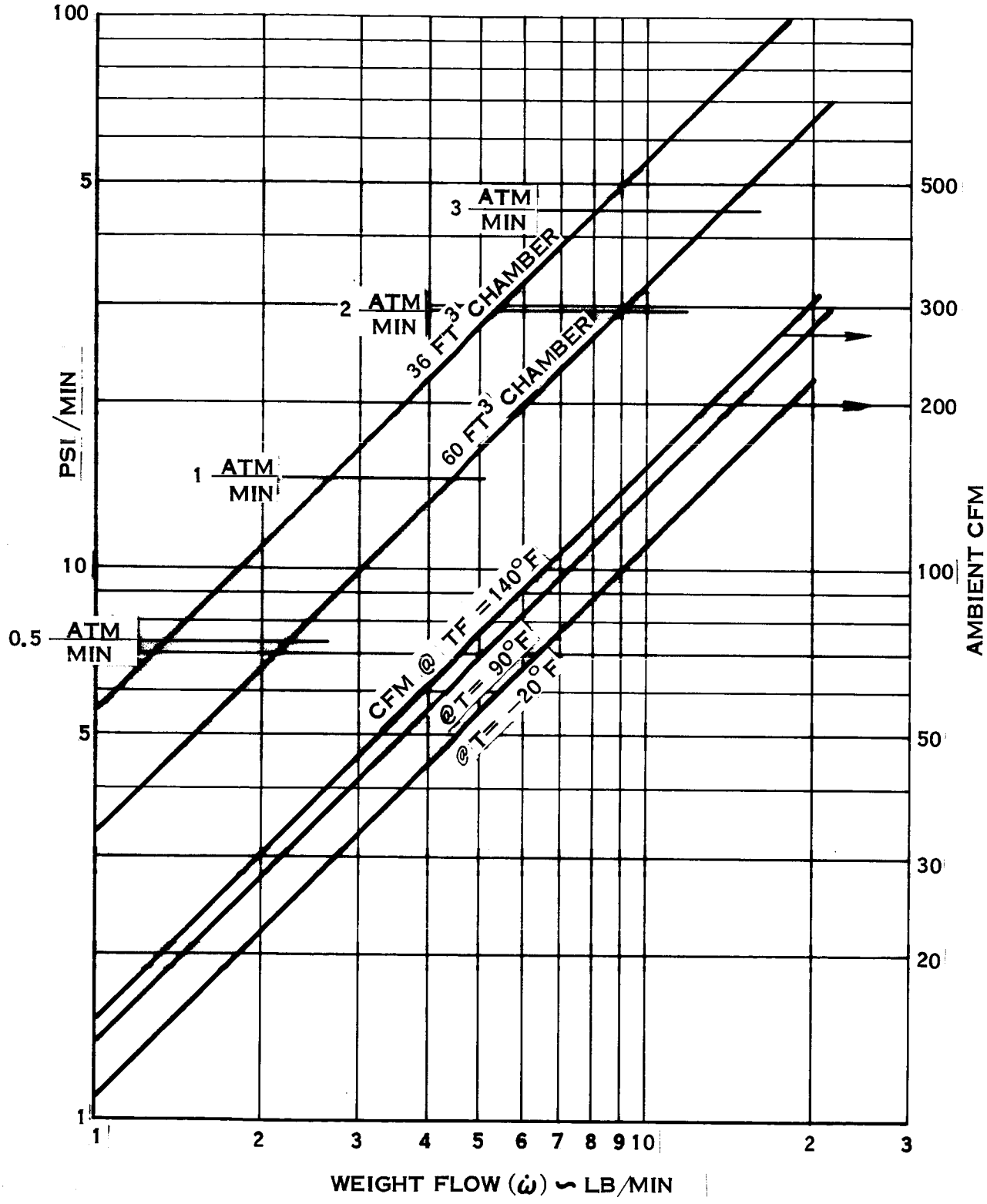


FIGURE 22. HYPERBARIC CHAMBER FILL RATES

1350 gm good for 14 hours @ CO_2 = 300 cc/min = 0106 cfm

$$\rho_{co_2} = \frac{15x144}{35.1x550} = .112 \text{ lb/ft}^3$$

W_{co_2} = (.0106)(60)(.112) = .0713 lb/hr x 14 hours = .998 $^{H}CO_2$/1350 GM
.335 $^{H}CO_2$/#SODASORB

LEM Canister can hold 5.4 x $\frac{38.3}{31}$ = 6.67 lb. SODASORB

6.67 x .335 $\frac{\#CO_2}{\#SODASORB}$ = 2.23 lb CO_2 Removal Capacity

Required Maximum for 8 hours @ 1400 btu/hr
$(.195 \times 10^{-4})$ (1400) (8) = 2.18 lb CO_2 to be removed

Pressure Drop @ W = 507.5 lb/hr 88.2 psia

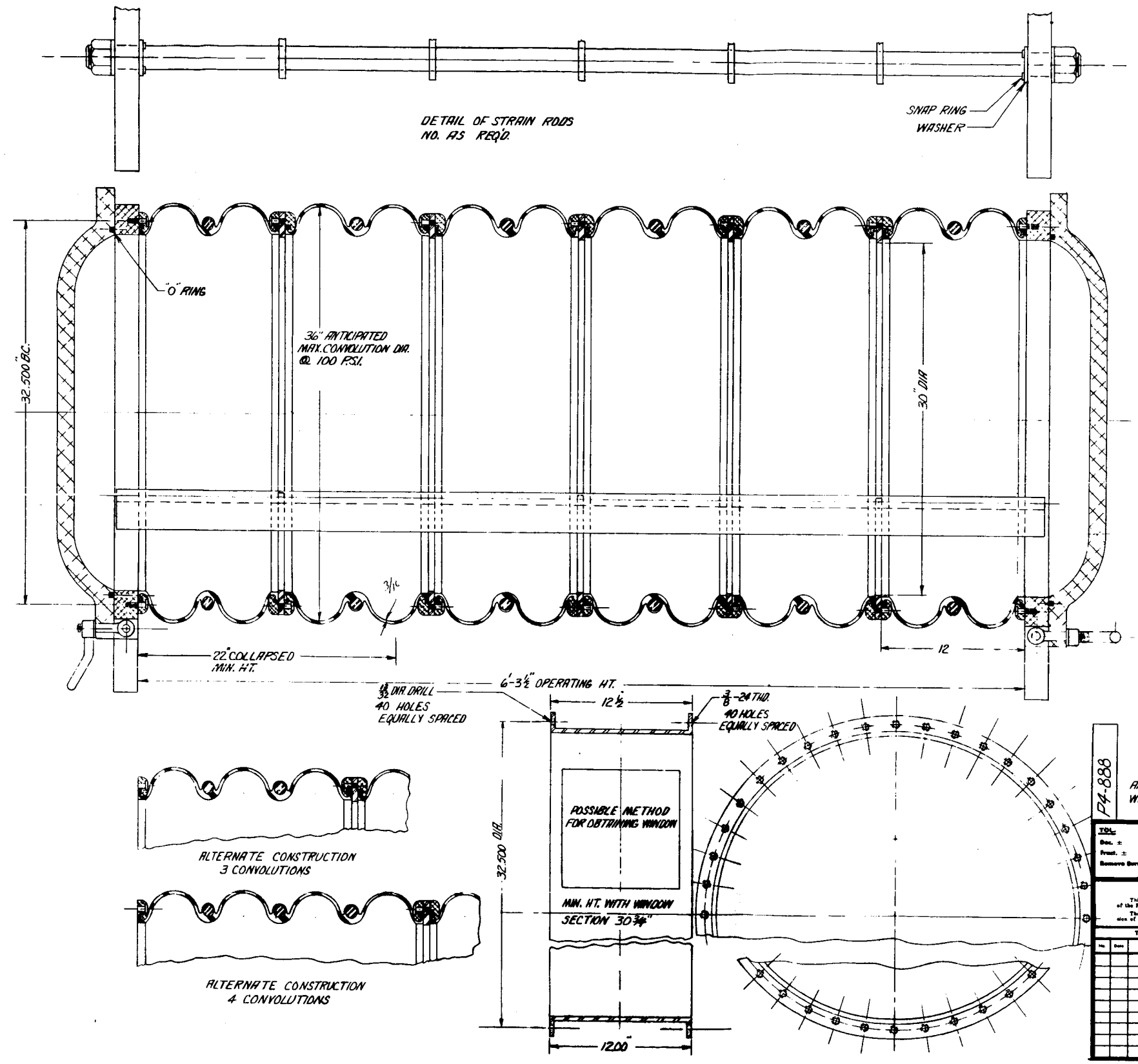
$\Delta P = .671 \text{ (lb/min)}^{1.38}$ in. H_2O, R = 49.4 (LEM Canister)

$$\Delta P = .671 \left(\frac{507.5}{60}\sqrt{\frac{49.4}{53.35}}\right)^{1.38} x \frac{.0765}{.445} = 2.10" \text{ } H_2O$$

Temperature rise @ Qmet = 1400 btu/hr, W = 507.5 lb/hr

$$N_AOH + KOH + CO_2 \longrightarrow NACO_3 + KCO_3 + H_2O + \frac{1230 \text{ btu/hr}}{\#CO_2}$$

$$\Delta T = \frac{Q}{W_{cp}} = \frac{1230 \text{ x } (195x10^{-4})(1400)}{507.5 \text{ x } .24} = 2.76°F.$$


DETAIL OF STRAIN RODS
NO. AS REQ'D.
SNAP RING
WASHER
"O" RING
36" ANTICIPATED
MAX. CONVOLUTION DIA.
@ 100 P.S.I.
32.500 B.C.
30" DIA
3/16
22" COLLAPSED
MIN. H.T.
12
6'-3½" OPERATING H.T.
12½
3/8-24 THD.
40 HOLES
EQUALLY SPACED
5/32 DIA. DRILL
40 HOLES
EQUALLY SPACED
POSSIBLE METHOD
FOR OBTAINING WINDOW
32.500 DIA.
MIN. HT. WITH WINDOW
SECTION 30¾"
12.00"
ALTERNATE CONSTRUCTION
3 CONVOLUTIONS
ALTERNATE CONSTRUCTION
4 CONVOLUTIONS
P4-888
ANTICIPATED MIN. BURST ABOVE 200 P.S.I.
WITH 2 PLY CONSTRUCTION
DO NOT SCALE
TOL.
Dec. ±
Unless Spec.
Fract. ±
Unless Spec.
Remove Burrs
MAT'L
REF. DWG.
216C-P4-854
This Drawing is the property of Firestone Industrial Products Co.
This drawing is issued with the express condition that it is not to be used in any way deleterious to the interests of the Firestone Tire & Rubber Company.
The acceptance of this drawing will be construed as an acceptance of the foregoing conditions, and as an admission of the exclusive ownership in and to the drawing of Firestone Industrial Products Company.
TABLE OF REVISIONS
No. Date Description Dwn Ck'd App'd
216C DECOMPRESSION CHAMBER
FOR UNITED AIRCRAFT
Firestone Industrial Products Company
DIVISION OF THE FIRESTONE TIRE & RUBBER COMPANY
MIDDLETOWN, INDIANA
Date 2-4-66
Drawn by JONES
Traced by
Checked by
Approved by
Date
Designed by
Scale QUARTER — 1 Pt.
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APPENDIX VI

APPENDIX VII

BASIC PHYSIOLOGIC MONITORING IN A HYPERBARIC CHAMBER

INTRODUCTION

The purpose of this section is to determine proper techniques of monitoring various physiological parameters in a hyperbaric environment. To satisfy this requirement, the section has been divided into three parts: a) A review of commercially available and experimental measurement devices in order to determine whether something already developed could be adapted for use in our abnormal environment, or whether somethine new must be developed to fulfill this need; b) Based upon criteria that must be met in order to establish adaptability, our selection of proper monitoring devices for the collapsible portable hyperbaric chamber; c) Other applications of the instruments reviewed in (a) in hyperbaric medicine.

Review of Physiologic Monitoring

The proposed physiological parameters of the patient to be monitored in a hyperbaric chamber are: blood pressure, body temperature, respiratory rate, electrocardiogram, and cardiac rate.

I. BLOOD PRESSURE

A. Sphygmomanometer

1. General

The standard method in use today to measure blood pressure is the sphygmomanometer. This consists of an inflatable cuff that is placed over the brachial artery on the forearm. The cuff is inflated to a pressure above the systolic pressure and then the gas is slowly let out until the diastolic pressure is reached, after which the remaining gas is dumped and the procedure repeats itself.. The cuff pressure can be measured by various transducers placed directly in the cuff. A microphone, strain gauge, or piezoelectric crystal can be used to detect the arterial sounds, when placed directly over the brachial artery, directly below the cuff, However, a strain gauge is affected by environmental temperature and therefore compensation would be required. Another type of transducer that could be used in place of the microphone would be a flexible-bladder containing fluid placed directly over the brachial artery and connected hydraulically to a pressure transducer.

2. Government Agency Applications

a. Vogt (1) in a NASA program used an E & M Company electro-shygmograph that consists of a pressure transducer and preamplifier producing single channel recordings of occluding cuff pressure and superimposing Korotkoff sounds. The cuff may be either inflated manually with an hand bulb or automatically when used with their cuff pump. The cuff pump contains its own air pump and has pressure sensitive cut-off switches for limiting upper level of cuff inflation to a variable 100 to 300 mm Hg. and preventing reinflation until cuff pressure drops below 20 mm Hg. The pump may be set for a single cycle or repeat cycles at half-minute, one-minute or two-minute intervals for continuous monitoring. The electrosphygmograph is calibrated with a panel-mounted 0-300 mm Hg. aneroid pressure gauge.

b. Smedal (2) at Ames Research Center, California, under a NASA Airborne physiological study in 1960, used an autosphymomanometer. This consisted of a standard 13 by 23 cm cuff, pressure source, manometer and stethoscope. The pilot's bail-out oxygen bottle containing nitrogen was used as the pressure source. The cuff inflated in 2 seconds using a USAF developed sequencing valve that discharged linearly for 20 seconds. This sequence was repeated every 30 seconds. The cuff pressure is measured by a 0-5 lb/in^2 strain gauge transducer and a standard dynamic earpiece acts as the stetho-scope. The stethoscope is connected to an amplifier with band pass between 150-200 cps whose output is added to the pressure transducer output and points noted where sound pulses due to heart beat are found. Accuracy is dependent upon heart rate during measuring sequence, and the slope of cuff discharge. pressure. The system is normally accurate with $\pm$ 4 mm Hg.

c. Kahn and Ware (3), at the School of Aerospace Medicine, Brooks AFB, Texas, have developed a system that automatically measured the systolic and diastolic blood pressure indirectly. They claim that it provides no encumbrance or annoyance to the subject and that neither body motion nor intense acoustical noise should interfere with the signal. A 5" metal-ribbed cuff with a differential type of cuff pressure transducer, referred to the ambient of the subject (Daystrom-Wiancko model P2-1336 differential transformer) is used. The microphone is the contact type (favoring structure conducted and rejecting air-donducted sound) of small size and mass (piezoelectric-Vibroceramics Division Gulton Industries, Glennite external cardiac microphone model MP-202 modified for this case). The pre-amplifier is small and connected by short leads to the microphone to minimize extraneous pick-up. The current drain is very small (75 ma-hr. mercury battery will power it

for 7500 hours of continuous operation). A microphone retention pad retains the microphone in optimum contact with the skin over the brachial artery and encloses both the pre-amplifier and battery.

Roman (4) compared data obtained by this method with that simultaneously obtained by arterial catheterization in flight and found it satisfactory even though the acoustic blood pressure readings were slightly lower than the other.

d. The School of Aerospace Medicine, Randolph AFB, Texas uses a graphic comparison obtained by superimposing the sound wave tracing on the original pressure plot. The Korotkoff sounds are filtered to exclude outside interference.

e. The AiResearch Manufacturing Company of Los Angeles, California developed a blood pressure measuring system that was used in Project Mercury. The only difference of this unit from the standard clinical instrument is that the stethoscope is replaced by a microphone and that the output is conditioned by amplifiers and filters. The output is recorded on a strip chart of cuff pressure versus time with the Korotkoff sound pulses superimposed. The first pulse denotes systolic pressure and the last diastolic pressure.

3. Other Applications

a. Geddes (5) developed an electrosphygmograph at Baylor University that also uses a sound transducer on the lower edge of a cuff. The Korotkoff sounds and the cuff pressure are electronically added in a single tube mixer unit.

b. The University of Michigan Medical School (6) is using a system manufactured by Propper Company of Long Island, New York, which employs a cuff which can be slid on or off like a bracelet when the proper size is determined. A guage and long connecting manometer tube are attached and a stethoscope end piece is incorporated in the cuff. This device has been manipulated by medically untrained people. However, it is not automated and this would have to be accomplished to make it operable for our application.

B. Finger Plethysmograph

1. General

Another method for measuring blood pressure, the finger plethysmograph uses an occluding rubber cuff around the subject's finger. At the tip of the finger is a sensor which picks up volumetric changes at the finger tip due to blood pulsation. The pulsations are amplified and used to operate a pneumatic system to inflate the cuff with air. When cuff pressure rises above systolic pressure, pulsations at the finger tip disappear and the cuff stops inflating. Air in the cuff bleeds out through a constantly open leak valve. When pressure falls below systolic, pulsations reappear and the cycle repeats.

2. Commercial Applications

Gulton Industries produces one where the cuff pressure starts at zero and is raised 5 mm Hg/second. At diastolic pressure, a plethysmogram wave shape change is detected by the sensor (dichrotic notch flattens out and broadens) and the pressure is recorded. Cuff pressure is then increased to systolic at which point the plethysmogram disappears and the pressure is recorded. Cuff pressure returns to zero and the process repeated. This same system, Gulton claims, can also be used to monitor heart rate and body temperature. The device is small and attachment quick and easy. According to Traite (7) test subjects reported the repetitive cycle is largely ignored after 5-10 minutes. Coreelation with brachial artery pressure measurements are within 5 mm Hg. Its adaptability to a Hyperbaric Chamber environment would appear to be the same as the physgmomanometer. Possible, compensation has to be made for lower pressure readings at an extremity.

C. Other Methods

1. Government Agency Applications

a. A transducer has been developed at the Stanford Research Institute (9) under a NASA contract to measure blood pressure on the temporal artery. Although outwardly this would appear to make other methods outmoded, this device is still in the experimental stage and a number of problems remain to be solved, one being positioning of the transducer on the artery, another the time required for calibration.

2. Experimental

a. Wood (8) has suggested the use of an ear oximeter to measure arterial blood pressure. Honeywell has manufactured such a device for research use only, as it has not been clinically proven yet.

3. Commercial Applications

a. American Electronic Laboratories, Inc., monitors blood pressure with an occluding arm cuff and a Korotkoff microphone and compares the signal with those received from an optical pulse pick-up placed on the finger tip and heart rate signals by means of computer logic circuitry. If the three analyzed signals are in correct number and order for three successive beats, the cuff pressure is locked and the meter displays systolic pressure.

The inflation range of the cuff is from 50-300 mm Hg. and the accuracy $\pm$ 3 mm Hg. The chief failure of this instrument for our purposes is that it does not measure diastolic pressure.

II. BODY TEMPERATURE

A. Skin

1. Government Agency Applications

Devices presently in use include one developed at the USAF - School of Aerospace Medicine, Brooks, AFB, Texas (10) which uses a thermistor in a hollow recessed Teflon button. The button is glued to the skin and covered with tape at a point between the wrist and the thenar. It is calibrated by substituting a series of known resistance values in place of the thermistor. From these values the temperature is determined from a curve of resistance versus temperature for each thermistor unit. To identify the magnitude and direction of subcarrier drift, it is suggested that a transistor should be substituted at regular interfals.

B. Rectal

1. Government Agency Applications

The Army (12) has developed a portable direct reading rectal thermistor probe that has a $\pm$ 0.1F^{o} accuracy. The device has been used on active subjects and according to the author presents no restrictions. The measurements may be made by a rather unskilled technician. The main disadvantages are:

1. A need for individual calibration of catheters.

2. The maintenance of a stock of resistors.

C. Oral

1. Commercial

a. Hi-G Corporation has introduced a battery operated thermometer. It is accurate within 0.2 of a degree, and the probe can be wrapped in a sanitary, disposable plastic sleeve for each use, thus avoiding the need for sterilization. Another advantage pointed out is that temperature may be taken without waking the patient.

b. The Yellow Springs Instrument Company manufactures thermistor probes for oral as well as rectal measurements. The probes are interchangeable with others in their "400" series with an accuracy of $\pm .2^{o}F$ and follow the same resistance temperature curve over their usable temperature range. They range in diameter from 1/8" tube to a .058" tube with a 13/32" disc on the end. The temperature range is from -110 to $+300^{o}F$, with time constants ranging from 0.8 to 3.4 seconds.

D. Other Methods

1. Experimental

a. Benzinger (13) has developed a thermocouple to measure body temperature at the tympanic membrane. This work has been further advance under a USAF contract in Finland (14). These measurements are highly accurate when compared to esophagal temperature, while rectal measurements were very inaccurate. The main area, I believe where further study must be done is the attachment in unconscious patients due to the fact that the probe must touch the membrane. Also, leakage must be provided due to the pressure change in the chamber.

b. In the X-15 study (11) temperature is measured both on the skin (Y.S.I. thermistor disk No. 409) and in the rectum (Y.S.I rectal probe No. 401). The placement of the measuring devices, calf, forearm, and abdomen, was chosen to try to approximate true mean skin temperature under warm conditions. Deviations in placement allows for specific determinations and does not require recalibrations of the thermistors.

III. RESPIRATION

A. Using EKG Electrodes

1. Government Agency Applications

a. Vogt and Lamont (1) used this method with the electrodes attached to an E & M Company impedance pneumograph. Two microamps are passed through the electrodes. The voltage across the electrodes is directly proportional to subject impedance. The voltage does not exceed 2 millivolts, r.m.s. at 25,000 cps. An internal coupling network permits EKG from the same set of electrodes simultaneously.

b. McCally (15) passed a high-frequency carrier (20-60 KC) through the body by means of electrodes on either side of the thorax and measured the change of impedance between the electroless. The carrier signals are of low intensity and high frequency to prevent sensory or lethal stimulation. The authors have designed the circuit to provide minimum power consumption, smallest possible size and weight, and the least encombrance to the subject. The circuit has been used in both telemetry and hard-wire set-ups. A variety of electrodes were tried and the adhesive-backed metal gauze electrode (Telectrode, Telemedic, Inc., Vector Manufacturing Company) was found to be most satisfactory. According to the authors the impedance respirometer provides a simple and reliable means of recording respiratory rate and a minimum of encumbrance to the subject. Also, the same pair of electrodes may be used to obtain an electrocardiogram. However, they point out that the disadvantages are base-line shifts due to changes in electrode impedance, subject movement artifact, and poor signal quality from obese subjects.

2. Other Applications

a. L. A. Geddes (16, 17) developed a device similar to this, an impedance Pneumograph that requires two electrodes around the sixth rib.

B. Face Mask Transducer

1. Government Agency Applications

a. A device of this general type was developed by Simons (3) for the School of Aerospace Medicine. They used a thermistor (V.E.C. type 34A2, which has a resistance of 3500 ohms ± 15% at 25°C with a temperature coefficient of -3.7%°C and a one-second time constant) embedded in

epoxy which also incorporated a spring wire clip which held the device just inside the orifice of one nostril, exposing it to the stream of respired air. However, this ignores the fact that one also breathes through the mouth.

b. C. E. Melton, Jr. (18) used a Yellow Spring thermistor probe (#812) inserted 3/4" in the left nostril, in a study for the F.A.A. The probe was connected to a Yellow Spring telethermometer bridge which produced a writing pen deflectionaas the inspired air cooled the thermistor, changing its resistance and unbalancing the bridge circuit.

c. Smedal, Holden and Smith (2) used a device that measures through a determination of oxygen mass flow by placing a strain gauge flow transducer in the low pressure oxygen line of a face mask between the regulator and the mask. In a full-pressure suit where the oxygen regulator is located on the helmet the transducer was placed in the high-pressure (70 psi) oxygen line. Another method also employed in this study was a thermopile anemometer which is sensitive enough to work at high pressures. A fast response time of 0.1 second is achieved.

2. Commercial

a. Honeywell markets a respiration thermocouple transducer nosepiece manufactured by ENSCO. It is constructed of stainless steel with a nylon end to house the thermocouples. The unit is 3" long with the end measuring 2" wide by 1 1/2" deep.

C. Chest Measurement

1. General

This entails encirclying the chest with a strap and measuring the change of chest circumference. The ends of the strap are connected to a strain gauge which provides electrical indications of chest expansion and contraction. The disadvantages of this method, however, are that it constricts breathing, creates abdominal expansion, and is difficult to calibrate because it is hard to locate the level where the maximum chest expansion occurs.

IV. ELECTROCARDIOGRAM AND HEART RATE

A. Electrocardiogram

1. Government Agency Applications

a. Vogt and Lamont (1) used electrodes developed by Day and Lippitt (NASA, Manned Spacecraft Center, Houston, Texas) that were attached

a. to the skin by either Eastman 9-10 glue or double-backed colastomy tape. The electrodes are stainless steel wire mesh, approximately 5/8" in diameter. They are connected to the signal conditioner by a coaxial type single-shielded wire with a shielded ground. The signal is amplified to 1.5 v by a Gulf Aerospace Amplifier.

b. Smedal, et. al., (2) used a similar set-up with a fuse-diode system network inserted to prevent shock. The electrodes and adhesive are similar to the ones used by N.A.A. in the X-15 physiological instrumentation package. The X-15 electrodes were made of Morel metal screen (24 mesh by 0.0007" by 7/8" diameter) and used Microdot shielded cables for leads. The electrodes conform with body contours. Placement was dependent on body regions least subject to inducing muscle movement artifacts, but at the same time able to pick up ECG signals most nearly identical to conventional clinical records. There is a 5 ma fuse in series with each skin electrode to protect the patient from electrical shock. Additional protection is provided by parallel-reversed silicone diodes between the electrodes and airframe ground. They provide voltage-limiting protection at 0.7 volts and protect against electrical transients which might not affect the fuses.

SUGGESTED METHODS OF MEASUREMENT

The criteria used to establish adaptability are:

1. Ability to withstand hyperbaric chamber pressure, temperature and humidity changes.

2. Ability to withstand shock and vibration.

3. Size and weight limitations.

4. Placement and attachment of pickup device with regard to the physical restrictions it imposes on the subject.

5. Calibration required before use.

I Blood Pressure

Blood pressure is normally recorded in terms of gauge pressure, which is the difference between cuff and atmospheric pressure. In a hyperbaric chamber where the environmental pressure is not equivalent to atmospheric pressure, all pressure readings must be converted to some common denominator so that they may be compared if the measuring device is inside the chamber.

A space and weight problem is created by the accessory equipment of most sphygomanometer systems. These include the pressure source and pump needed to inflat the cuff. If the system is automated, environmental noise and vibration can create erroneous signals. The finger plethysmograph is unsatisfactory due to its method of reading diastolic pressure using the diehrotic notch. Unfortunately, not all subjects exhibit this characteristic.

Due to the failure of these automated sophisticated devices to meet our requirements, it is suggested that the standard manual device such as the E&M Company electrosphygmograph, with the pump on the outside of the chamber attached to the arm cuff through a pneumatic tube would be the most appropriate blood pressure measuring device for our system.

II BODY TEMPERATURE

The two most important areas to be considered for temperature measurement are location and method of attachment to the body. With skin sensors attachment is a problem. If they are attached too loosely, the temperature of the surrounding air rather than the skin is picked up. If too much pressure is used, they may become partially embedded in the surface of the skin, affecting the readings by causing local irritation. Also, the temperature is not the same at all points on the surface of the body. If surface measurements must be made, the axilla is probably the most stable point.

As the state-of-the-art stands today, rectal measurements probably give the most reproducible data. They can be inserted a specific distance and taped in place, however, due to the location and discomfort they cause they are unsuitable for our purpose.

Therefore, although they are not the most accurate means of measurement are limited to an oral measurement in a hyperbaric chamber such as the Yellow Spring thermistor probe or the Hi-G probe. When a device is properly developed it would appear that the tympanic membrane offers the greatest promise as a location for a temperature measurement due to its proximity to the body thermostat, thereby providing accuracy and unencumbrance to the patient.

III RESPIRATION

It would appear that both the impedance pneumograph and the thermistor nasal clip meet the established criteria, whereas the ease of application is greater with the nasal clip the electrodes used with the pneumograph serve the dual purpose of measuring electrocardiogram as well as respiratory rate.

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT · U.S.A.

September 7, 1966

National Aeronautics and Space Administration
Washington, 25, D. C. 20546

Attention: Mr. V. B. Kurkjian, Contracting Officer (Code M-SC) - (1 copy)

Subject: Contract NASW-1271 - Final Report

Gentlemen:

In accordance with the subject contract, six copies of the Final Report and two hyperbaric chamber scale models were submitted to the Office of Technology Utilization on March 28, 1966 in conjunction with a final presentation of the contract work. At that time, it was our understanding that comments and/or suggested revisions to the submitted report would be forthcoming from NASA within a reasonable time. To date, such comment has not been received. A number of informal attempts by Hamilton Standard to elicit such comments have been unsuccessful.

Considering that no adverse comments have been received in the elapsed time period, we have assumed that the report is acceptable. Therefore, in accordance with Article VI(B), (F), Hamilton Standard herewith submits twenty-five (25) copies of the Final Report for Contract NASW-1271. Inasmuch as all requirements of the contract have been satisfied, an invoice will be submitted for the contract amount.

Very truly yours,

HAMILTON STANDARD
Division of United Aircraft Corporation

W. F. O'Connor
Contracts Administration

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